Fisheries and Oceans Canada
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Canadian Science Advisory Secretariat (CSAS)

Research Document 2014/047

Maritimes Region

Indicators of Pelagic Habitat Status in the Northwest Atlantic

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October 2014

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044

Correct citation for this publication:

Johnson, C., Pepin, P., Curtis, K.A., Lazin, G., Casault, B., Colbourne, E., Galbraith, P.S., Harvey, M., Herbert, D., Maillet, G., and Starr, M. 2014. Indicators of Pelagic Habitat Status in the Northwest Atlantic. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/047. v + 74 p.

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ABSTRACT

Regional changes in pelagic (i.e. water column) habitat, including the physical and chemical environment and plankton abundance and community composition, may influence productivity of fisheries at regional scales. The analysis presented here used principal component analyses (PCA) to characterize the dominant patterns of variability in zooplankton communities and the environment at the scale of the Canadian northwest Atlantic continental shelf system from the Labrador Shelf to the eastern Gulf of Maine. The analyses used data collected by the Atlantic Zone Monitoring Program in Fisheries and Oceans Canada's Newfoundland, Gulf, Québec, and Maritimes regions. As a case study on using pelagic habitat status indicators to understand variability in fishery status, the principal component scores, climate indices and sub-regional-scale environmental and plankton metrics were compared with interannual changes in the distribution, condition, and recruitment of eastern Gulf of Maine and Scotian Shelf herring. The zooplankton PCAs in spring and fall identified depth and cross-shelf associations as the dominant mode of community variability, followed by temperature and seasonal associations and regional differences between the Gulf of St. Lawrence and open shelf communities. The environmental PCAs in spring and fall identified variability in nutrient inventories as the dominant mode of variability, with high values in the northwest Gulf of St. Lawrence in both seasons and north of the Grand Bank in spring. The second mode of environmental variability generally differentiated warm, salty deep water from shallow water with higher excess nutrients in both seasons, while the third mode was associated with higher chlorophyll and lower excess silicate in cooler waters and differentiated the Newfoundland Shelf and Grand Bank from the Gulf of St. Lawrence in spring and from the Scotian Shelf in fall. Herring condition metrics in the Scotian Shelf subregions were positively correlated to one another and negatively correlated to herring distribution on the Eastern Scotian Shelf. Scotian Shelf herring were generally in better condition under cooler, higher nutrient environmental conditions consistent with increased outflow from the Gulf of St. Lawrence onto the Scotian Shelf. Eastern Gulf of Maine herring metrics had few consistent correlations to environmental factors, suggesting that the condition and recruitment of these stocks, sampled on their spawning grounds, did not have a common response to large scale pelagic habitat variability. However, the dominant copepod species *Pseudocalanus* spp. and, to a lesser extent, *Calanus finmarchicus*, known to be important prey for herring, were positively correlated to many herring metrics in ordered factors correlation analyses, which emphasize extreme values of the herring and environment metrics. The influences of large-scale and regional processes on the shelf system were evident in the patterns that emerged from the zooplankton and environmental multivariate analyses. The short time series available had low power to identify relationships between pelagic habitat and herring metrics, but allowed the identification of relationships that could be further examined using longer time series of representative environmental metrics.

Indicateurs de l'état de l'habitat pélagique dans le nord-ouest de l'Atlantique

RÉSUMÉ

Les changements régionaux dans l'habitat pélagique (i.e. colonne d'eau), incluant l'environnement physique et chimique ainsi que l'abondance et la composition de la communauté du plancton, peuvent influencer la productivité des pêches à l'échelle régionale. L'analyse en composantes principales (ACP) a été utilisée ici pour caractériser les modes dominants de la variabilité dans les communautés de zooplancton et dans l'environnement à l'échelle du plateau continental canadien du nord-ouest de l'Atlantique, depuis le plateau continental du Labrador jusqu'à l'est du Golfe du Maine. Les analyses ont utilisé les données recueillies dans le cadre du Programme de Monitorage de la Zone Atlantique de Pêches et Océans Canada dans les régions de Terre-Neuve, du Golfe, du Québec et des Maritimes. Dans le cadre de l'étude de cas sur l'utilisation des indicateurs de l'état de l'habitat pélagique pour expliquer la variabilité de l'état des pêches, les scores des composantes principales, les indices climatiques et les indices environnementaux et du plancton à l'échelle sous-régionale ont été comparés aux changements interannuels de la distribution, de l'état et du recrutement du hareng dans l'est du Golfe du Maine et sur le plateau néo-écossais. L'ACP des données de zooplancton au printemps et à l'automne a identifié la profondeur et les associations perpendiculaires au plateau comme mode dominant de la variabilité de la communauté, suivie par la température et les associations saisonnières et les différences régionales entre les communautés du Golfe du Saint-Laurent et celles au large du plateau. L'ACP des données environnementales au printemps et à l'automne a identifié la variabilité de l'inventaire d'éléments nutritifs comme mode dominant de la variabilité de l'environnement, caractérisé par des valeurs élevées dans le nord-ouest du Golfe du Saint-Laurent dans les deux saisons et au nord du Grand Banc au printemps. Le second mode de variabilité de l'environnement a distingué généralement l'eau salée chaude et profonde de l'eau peu profonde montrant un excès plus élevé d'éléments nutritifs dans les deux saisons, tandis que le troisième mode était associée à une plus haute concentration de chlorophylle et un excès moins élevé en silicate dans les eaux plus froides et a différencié la région du plateau de Terre-Neuve et du Grand Banc de la région du Golfe du Saint-Laurent au printemps et de celle du plateau néo-écossais à l'automne. Les indices de l'état du hareng dans les sous-régions du plateau néo-écossais étaient positivement corrélés entre eux et négativement corrélés à la distribution du hareng dans la partie est du plateau néo-écossais. La condition du hareng sur le plateau néo-écossais était généralement supérieure sous les conditions environnementales plus froides et plus riches en éléments nutritifs résultant du débit plus important du Golfe du Saint-Laurent sur le plateau néo-écossais. Les indices du hareng dans l'est du Golfe du Maine étaient peu corrélés aux facteurs environnementaux, suggérant que l'état et le recrutement de ces stocks, échantillonnés à même leurs lieux de fraye, n'ont pas démontré une réponse généralisée à la variabilité de l'habitat pélagique à grande échelle. Toutefois, les espèces dominantes de copépode *Pseudocalanus* spp. et, dans une moindre mesure *Calanus finmarchicus*, reconnues comme proie importante pour le hareng, étaient corrélées positivement à de nombreux indices du hareng dans l'analyse de corrélation des facteurs ordonnés mettant l'accent sur les valeurs extrêmes des indices du hareng et de l'environnement. Les tendances résultant des analyses multivariées des indices du zooplancton et de l'environnement ont clairement démontré l'influence des processus régionaux et à grande échelle sur le système du plateau continental. La durée relativement restreinte de la série temporelle des données a limité l'identification de relations entre les indices de l'habitat pélagique et ceux du hareng, mais a toutefois permis d'identifier des relations qui pourraient être examinées plus en profondeur en utilisant une série temporelle plus longue d'indices environnementaux représentatifs.

INTRODUCTION

There is substantial evidence that changes in oceanic gyres and continental shelf circulation can result in regional changes in pelagic (i.e. water column) habitat characteristics such as temperature, productivity, seasonal timing, or availability of appropriate prey, due to shifts in frontal and biogeographic boundaries, and that these changes can either reduce or enhance the productivity of fisheries at regional scales (Beaugrand et al. 2003, Frank et al. 1996, Hatún et al. 2009). These changes, in addition to surface ocean warming trends, represent variable external ecosystem drivers of thermal habitat and lower trophic level (i.e. phytoplankton and zooplankton) productivity that must be considered in management decisions, in combination with knowledge of the responses of fish stocks to changes in their environment, to avoid negative social, economic, and ecological outcomes (OECD 2010). While variability in large-scale environmental forcing cannot be managed, incorporation of information about pelagic habitat status can help to mitigate its impact through changes in managed activities. The NW Atlantic shelf system is influenced by processes at multiple scales, but there is clear evidence of large-scale coherence in the response of the physical environment (Petrie 2007) and fish distributions (Fisher et al. 2008) to large-scale processes such as atmospheric forcing.

The pelagic indicators project aimed to develop a protocol for reporting the dominant patterns of large-scale variability in the pelagic habitats of the NW Atlantic shelves from the Labrador Shelf to the Mid-Atlantic Bight, using environmental and biological data from the Newfoundland, Québec, and Maritimes regions of the Atlantic Zone Monitoring Program (AZMP). The primary objective was to succinctly communicate information gathered by AZMP about large scale shifts in pelagic habitat status, related to changes in atmospheric forcing, circulation and biogeographic zones, to resource managers, stock assessment scientists, and other interested parties. Since many of the physical, chemical, and biological properties measured by AZMP can co-vary, a multivariate statistics approach was used to evaluate the relationships among variables and to develop a limited number of indicators to describe significant large-scale ecosystem processes (Levin et al. 2009). Emphasis was placed on developing indicators that best represent the response of the physical and chemical environment to large-scale climate forcing and lower trophic level vulnerability to climate-driven environmental variability and change.

For indicators of environmental pressures to be useful for informing management decisions, it is necessary to know their relationships to fisheries responses (Jennings 2005). As a case study on using pelagic habitat status indicators to understand variability in fishery status, the pelagic habitat status metrics developed by this project, as well as climate indices and sub-regional-scale environmental metrics, were compared with interannual changes in the distribution, condition, and recruitment of eastern Gulf of Maine and Scotian Shelf herring. Herring and other planktivorous small pelagic fish populations can be sensitive to large scale changes in environmental conditions (e.g. Frank et al. 1996, Winters and Wheeler 1987), but they are also influenced by smaller-scale environmental variability. The analysis presented here developed indicators of pelagic habitat variability and used a case study to evaluate how they can be used to provide relevant information for use by stock assessment scientists and fisheries managers. The methods developed in this project are intended to be incorporated into future AZMP reporting and to enhance the value of AZMP data to management.

DATA

The pelagic indicators project employed data collected during 13 years of AZMP sea-going missions. The AZMP is the largest NW Atlantic monitoring program for the pelagic environment, covering an area from the Labrador Shelf to the Gulf of Maine. It was implemented in 1998 with the aim of:

1. increasing Fisheries and Oceans Canada's (DFO's) capacity to understand, describe, and forecast the state of the marine ecosystem, and
2. quantifying the changes in ocean physical, chemical, and biological properties and the predator—prey relationships of marine resources (Therriault et al. 1998).

The AZMP derives its information on the state of the marine ecosystem from data collected at a network of sampling locations (fixed point stations, cross-shelf sections, trawl surveys) in each DFO region (Québec, Gulf, Maritimes, Newfoundland) sampled at a frequency of twice-monthly to once annually. The sampling design provides for basic information on the natural variability in physical, chemical, and biological properties of the Northwest (NW) Atlantic continental shelf. The analysis presented here focused on physical, biological, and chemical data collected on the 14 AZMP cross-shelf sections during spring and fall missions by the Maritimes, Québec, and Newfoundland regions for the time period 1999-2011 (Figure 1).

The dataset included 77 missions (25 by Maritimes, 26 by Newfoundland and 26 by Québec region), with more than 3400 sampling events. Although spring and fall surveys are performed in all three regions, the AZMP sections are not sampled simultaneously among the regions or at exactly the same time each year within the regions. Newfoundland spring surveys were frequently sampled in April-May before or during the spring bloom, while April-May Maritimes surveys typically followed the bloom, and Québec surveys were most often in June, much later than the bloom (Figure 2). The fall surveys were typically in September/October for Maritimes, in October/November for Québec and November/December for Newfoundland. These regional and interannual differences must be considered in interpreting large-scale pattern in environmental and lower trophic level variability. A list of all the section stations involved in this study is included in Appendix A.

The details of data collection strategies and methods can be found in the AZMP reports and protocols (Mitchell et al. 2002). A brief description of the subset of the AZMP data set used in the analysis is provided below.

ENVIRONMENTAL DATA

Environmental variables were derived from CTD (Conductivity, Temperature, and Depth) profiles of temperature, salinity and oxygen and from profiles of nutrient (nitrate, phosphate, and silicate) and chlorophyll concentrations from water samples collected at a standard set of depths. In order to standardize the products for all the regions, the variables were derived using common processing strategies and protocols established by the AZMP synthesis working group.

As part of the standardization, nominal station depths were assembled for each standard station location. Use of nominal depths is preferable for consistent estimation of near-bottom and averaged properties, as described below. Nominal depths in the Maritimes Region were determined using statistical analysis of the depth measurements during AZMP missions along with bathymetry data available in various databases. A table of nominal depths at the standard section station locations is included in Appendix A, and a summary of the analysis to determine nominal depth in the Maritimes is presented in Appendix B.

CTD data sets were assembled by physical oceanographers in the three regions. Chlorophyll and nutrient data were either extracted from DFO's database BioChem, the national repository for biological and chemical marine environmental measurements, or provided by participating

investigators in cases where AZMP data have not yet been loaded into BioChem (DFO 2013). A summary of the procedure used to compile environmental data that were measured using different methods is included in Appendix C. Although there are standard quality control procedures for the different data types, application of quality control procedures has not yet been consistently applied (most notably observed in the regional differences in standard deviation of seasonal anomalies of average oxygen concentrations in Appendix E Figure E.10). For this project, informal quality checks were performed by the investigators and technical staff for all data.

A set of standard environmental variables was defined by the AZMP synthesis working group to summarize and characterize environmental variability in the region. Those variables were computed for each station occupation and consist of physical, nutrient and chlorophyll parameters.

The physical variables derived from CTD data include the following:

Average seawater temperature, 0-50 m (T0_50) (°C)

Average salinity, 0-50 m (S0_50) (psu)

Stratification index (STRAT) (kg m^{-3})

Average dissolved oxygen concentration, 0-50 m (O2_050) mL L^{-1}

Bottom temperature and salinity (T_NB and S_NB) (°C and psu)

Minimum temperature for each profile and the depth of minimum temperature (°C and m)

Cold Intermediate Layer (CIL) thickness (m)

The variables derived from the bottle profiles include:

Integrated nitrate concentration in the surface (0-50 m) and deep (50-150 m) layers (NIT0_50 and NIT50_150) (mmol m^{-2})

Integrated silicate concentration in the surface (0-50 m) and deep (50-150 m) layers (SIL0_50 and SIL50_150) (mmol m^{-2})

Integrated phosphate concentration in the surface (0-50 m) and deep (50-150 m) layers (PHO0_50 and PHO50_150) (mmol m^{-2})

Integrated chlorophyll concentration, 0-100 m (CHL0_100) (mmol m^{-2})

Excess silicate, 0-50 m (XSIL0_50) (mmol m^{-2})

Excess phosphate, 0-50 m (XPHO0_50) (mmol m^{-2})

The physical variables were computed by the physical oceanography teams in the three regions using common processing strategies. If the nominal station depth was less than 50 m, the average water temperature, salinity and dissolved oxygen in the surface layer were computed from 0 m to the nominal depth. The stratification index was determined as the density difference between 5 and 50 m (or nominal depth). Due to variability in CTD profile depths, bottom temperatures and salinities were reported if measured within 95%, 90% and 85% of nominal depth for Maritimes, Newfoundland, and Québec Regions, respectively. Due to spatial differences in deep-water temperature among the three regions, the regional index of the cold intermediate layer (CIL) was reported as the thickness of a layer in the water column with temperature less than 0°C for Newfoundland, less than 2°C for Québec and less than 4°C for Maritimes Region.

Integration of the nutrient and chlorophyll profiles to generate shallow and deep-water averages was performed using a trapezoidal integration procedure. The integration function, developed in Matlab and used to integrate bottle data from all three regions, is described in detail in Appendix

D. At stations where the nominal depth was less than the bottom depth of the desired layer (50 or 150 m), the integration was performed to the nominal depth instead. Excess silicate in the layer 0-50 m was computed as the difference between silicate and nitrate concentrations in the layer (Silicate – Nitrate) and excess phosphate computed according to the following equation:

$$\text{Excess Phosphate} = (\text{Phosphate Concentration}) - (\text{Nitrate Concentration})/16 \qquad (1)$$

The final environmental dataset was obtained by merging chlorophyll and nutrient variables with the physical parameters. The final merged dataset contains 684 sets of variables for Maritimes, 1115 for Newfoundland and 1136 for Quebec, a total of 2935 records for all regions.

To spatially visualize the final environmental dataset, maps of the seasonal mean values and the standard deviation of the seasonal anomaly at each station were created for each of the 18 environmental variables (Appendix E). The seasonal anomaly was determined using a reference period 1999-2010 and was computed for each station only if there were more than four years of data in the reference period. A low threshold number of years was chosen to include most of the stations and thus get a better idea about spatial variability in the larger area. Appendix E presents plots of the seasonal variables and an additional plot of the depth of the temperature minimum only at stations where it is less than 125 m, to emphasize the spatial variability in the depth of the CIL.

ZOOPLANKTON DATA

Zooplankton abundances were either extracted from the BioChem database or provided by project principal investigators, if data were not loaded in BioChem (DFO 2013). Species names were updated based on the World Register of Marine Species (WoRMS), using the WoRMS Taxon Match Tool (Appeltans et al. 2012). In the AZMP zooplankton analysis protocol, individual zooplankters are identified to the lowest level possible. Adult copepods and late-stage copepodites were usually identified to the species level, while early- and mid-stage copepodites were more typically identified to the genus level. Non-copepods were identified to the species level if possible, but differences in taxonomic resolution among regions and analysts tend to be greater for the non-copepods than for the copepods.

For this analysis, non-copepods were grouped into coarse taxonomic groups for more consistent representation among years and regions. Rare taxa were left out of the analysis, based on occurrence, defined as the percentage of station occupations at which the taxon was present. In general, taxa with 3% occurrence or greater in one or both seasons in at least one region were included in the analysis. For copepod genera with only one species observed in the AZMP regions, the genus and species were grouped and included in the analysis if one or both had at least 3% occurrence in one or both seasons in at least one region. For copepod genera with multiple species observed in the AZMP regions, genus and species groups were included individually if they had at least 3% occurrence in one or both seasons in at least one region. Exceptions include *Clausocalanus* spp. (genus and species grouped together due to taxonomic uncertainties that could bias analysis), the genus *Oncaea* (excluded from the analysis, because some but not all species in the region are now classified as *Triconia* spp.), *Pseudocalanus* spp., *Corycaeus* spp., and Aetideidae (each genus or family was grouped together, as species identifications are uncommon in some or all regions), and Euchaetidae (omitted).

An atlas of climatological spatial distributions of the taxa included in the analysis will be published separately.

MULTIVARIATE ANALYSIS RESULTS

To reveal the patterns in the distribution of zooplankton community structure, a series of multivariate analyses were performed, aimed to first provide an exploration of the major trends in composition and followed by an assessment of the influence of environmental variables that

we had hypothesized should be important influences on plankton distributions. Analyses were performed on the spring and autumn datasets separately because each represents a different phase in the seasonal succession of taxa and developmental stages.

Unconstrained analyses of the environmental and zooplankton community datasets were performed separately using Principal Component Analysis (PCA), which aims to represent the data along a reduced number of orthogonal axes that represent the main trends of each dataset. By treating environment and community separately, these analyses allowed us to identify the general spatial structure across the region. PCA is a passive form of analysis and the interpretation is done *a posteriori*. A preliminary evaluation of the environmental variables demonstrated significant differences in the underlying distribution of values, which would have significantly influenced the accuracy of our analyses. As a result, a fourth root transformation was applied to deep (50-150 m) nutrient inventories, and log-transformation was applied to depth, temperature (+2°C), stratification, CIL thickness (log or 0), surface (0-50 m) nutrient inventories, and chlorophyll (0-100 m) inventories. Oxygen concentrations, salinity and excess nutrient estimates were not transformed. A fourth root transformation was applied to the zooplankton abundance data.

ENVIRONMENTAL CONDITIONS

The pattern of variation during the spring surveys was strongly associated with both surface and deep nutrient inventories along the first principal component (PC), with greater loadings (i.e. eigenvector coefficients) in the deep strata (Figure 3A). There were strong inverse loadings of salinity with stratification, excess silicate, and thickness of the CIL along PC2 (Figure 3A). PC3 revealed that higher chlorophyll concentrations occurred in areas with cooler temperatures and weaker stratification, but higher phosphate and oxygen concentrations, patterns which are in keeping with photosynthetic oxygen production by silicate-dependent diatom communities (Figure 3B). Together, the first three PCs explain 62.8% of the variation in environmental variables from the spring surveys.

The spatial distribution of the average spring PC scores for each station revealed patterns in the environmental associations (Figure 3C-E). Positive PC1 scores occurred mainly in the deep water to the north and east of the Grand Bank and in the deep waters of the northwest Gulf of St. Lawrence , and off the Scotian Shelf (Figure 3C). Negative PC2 scores were associated with the deep water off the Newfoundland and Scotian Shelves but also occurred along the Southeast (SE) Grand Banks and Flemish Cap transects (Figure 3D). Negative PC3 scores mainly occurred on the Newfoundland Shelf and inshore Eastern Scotian Shelf (ESS), while positive PC3 values occurred at most stations inside the Gulf of St. Lawrence and in deep water off the Scotian Shelf and Tail of the Grand Banks.

The patterns of variation explained by the first three PCs of the fall survey data account for 66.1% of the overall variance, but the separation of variables indicated that the observations reflect a complex set of interactions relative to the patterns observed in spring (Figure 4A). Nutrient inventories, CIL thickness, and oxygen concentrations loaded positively along PC1, in opposition to the average temperature and salinity in the surface layer. However, nutrient inventories in surface and bottom layers showed separation along PC2, with higher bottom inventories occurring in the more saline deeper parts of the region. Higher chlorophyll inventories demonstrated an association with higher surface salinity and oxygen concentrations, along PC3 and were inversely related to stratification and excess silicate (Figure 4B).

The spatial distribution of the fall PC scores was generally similar to those in spring. (Figure 3C-E; 4C-E). However, the occurrence of positive PC1 scores was limited to the inshore Newfoundland Shelf and throughout the Gulf of St. Lawrence, and PC1 scores were negative at stations east of the Grand Bank as well as along the SE Grand Banks section and all sites on the Scotian Shelf (Figure 4C). Positive PC2 scores were found mainly in deep waters off the

shelf and in the deep channels of the Gulf of St. Lawrence (Figure 4D). Positive PC3 scores occurred on the Labrador and Newfoundland Shelves and the Grand Bank, while PC3 was mainly negative on the Scotian Shelf and in the Gulf of St. Lawrence (Figure 4E).

ZOOPLANKTON COMMUNITY

Spring Surveys

The first three PCs explained 43.5% of the variance (PC1 20.5%; PC2 13.6%; PC3 9.4%) beyond which only PC4 and PC5 explained more than 5% of the variance (Figure 5A, B). The pattern of loadings on the first two PCs among species was dome-shaped (Figure 5A), suggestive of a degree of non-linearity in the relationships among species but which could not be resolved by the use of other transformations to the data. *Pseudocalanus* spp., *Temora longicornis* and Larvacea had the strongest negative loading on PC1 while *Oithona* spp., *Microcalanus* spp., *Scolecithricella minor*, *Euchaeta* spp. and Ostracoda had the strongest positive loadings (Figure 5A). Bivalve and polychaete larvae had negative loadings on PC1. *Metridia lucens*, Euphausiacea and *Calanus finmarchicus* had strong positive loadings on PC2 while *Oithona* spp. and Cirripedia had weak negative loadings. The third PCs highlighted the separation of *Oithona* spp. and *Oithona atlantica* from *Paraeuchaeta norvegica*, *Triconia borealis*, Cnidaria and Ostracoda (Figure 5B).

The spatial distribution of the average scores for each station revealed clear patterns in the taxonomic assemblages (Figure 5C-E). Positive PC1 scores occurred principally beyond the continental shelf (defined by the 200 m isobaths) and in the deep channels of the Gulf of St. Lawrence where there was a weak but notable distinction with sites in shallower waters which had small negative average scores (Figure 5C). Average PC2 scores appeared to distinguish sites off Newfoundland (negative) with those from the Scotian Shelf and the deep channels of the Gulf (positive) (Figure 5D). Sites along the Bonne Bay, St. Lawrence Estuary and Magdelan Shallows sections also had moderate negative loadings suggesting that zooplankton assemblages at these locations were more similar to those off Newfoundland than to communities sampled on the Scotian Shelf and in the remainder of the Gulf. Sites with negative average PC3 scores were located mostly in the Gulf of St. Lawrence while sites with positive averages were located principally at sites in the Atlantic Ocean (Figure 5E). There were a few sites with weak positive average PC3 scores on the Grand Banks and at stations near the eastern coast of Newfoundland.

Fall Surveys

The first three PCs explained 46.9% of the variance in the fall dataset (PC1 – 20.6%; PC2 – 15.1%; PC3 – 11.2%) beyond which only PC4 and PC5 explained more than 5% of the variance (Figure 6A, B). The loadings of individual taxa were more uniformly distributed on PC1 and PC2 than in the analysis of the spring dataset. *Pseudocalanus* spp., *T. longicornis*, *Centropages* spp. and Bivalvia had the strongest negative loading on PC1 while *Oithona* spp., *Microcalanus* spp., *O. atlantica* and Ostracoda had the strongest positive loadings (Figure 6A). *Oithona* spp., *Metridia* spp. and *C. finmarchicus* had the strongest negative loadings on PC2 whereas warm-water species *Paracalanus* spp., *M. lucens*, *Centropages typicus* and *Clausocalanus* spp. had the strongest positive loadings. Positive loadings on PC3 were characterized by greater abundance of *Calanus hyperboreus*, *Oithona similis*, *T. borealis*, *Metrida longa* and Ostracoda while sites with negative loadings were associated with higher abundance of *Oithona* spp., *Paracalanus* spp., *O. atlantica* and *Clausocalanus* spp. (Figure 6B).

The spatial distribution of the average PC scores for each sampling location from the fall surveys were generally similar to those apparent in the spring (Figure 5). Positive PC1 scores occurred principally beyond the continental shelf (defined by the 200 m isobaths) and in the deep channels of the Gulf of St. Lawrence, which had the same distinction from the shallow

sites adjacent to those channels (Figure 6C). In contrast to the PC2 pattern noted in the spring, there appeared to be some distinction between most of the sites off Newfoundland and in the Gulf of St. Lawrence (negative scores) from those on the southern Grand Banks, Scotian Shelf and Cabot Strait (positive scores) (Figure 6D). Average PC3 scores were nearly all negative at sites in the Atlantic Ocean, while most of the PC3 scores were positive in the Gulf of St. Lawrence (Figure 6E).

Overall Summary

The zooplankton PCAs in both spring and fall picked up the dominant influence of depth in PC1. This was even apparent in the delineation of communities associated with the Laurentian Channel in the Gulf of St. Lawrence. The dominant shallow water species had the strongest negative loadings on PC1 in both seasons. The loadings on PC2 were quite asymmetrical in the spring, and they were also fairly different between the two seasons. Nevertheless, the spatial distribution of PC2 is similar between the two seasons. The second PC appeared to be more related to temperature, which varied both spatially and seasonally. Species with the strongest positive loadings on PC2 in the fall were all warm water species in the AZMP region. The asymmetrical distribution of loadings on PC2 in spring may reflect seasonally-driven spatial differences in abundance – the Newfoundland Shelf region was frequently sampled during the spring bloom when zooplankton abundances tend to be increasing, while the Scotian Shelf was usually sampled after the bloom and the Gulf of St. Lawrence was sampled well after the bloom (Figure 2). PC3 seemed to differentiate the Gulf of St. Lawrence from stations outside the Gulf, with positive loadings (outside) on *Oithona* spp. and *O. atlantica* and negative loadings (inside) on *Paraeuchaeta norvegica*, *Triconia borealis*, Cnidaria, and Ostracoda in spring. In fall, PC3 had positive loadings (inside) on *C. hyperboreus*, *O. similis*, *T. borealis*, *M. longa*, and Ostracoda and negative loadings (outside) on *Oithona* spp., *Paracalanus*, and *O. atlantica*.

In contrast to the zooplankton PCA, the environmental PCA picked up the dominant influence of nutrient concentrations on PC1 in both spring and fall. The spatial distribution of PC2 appeared to reflect the influence of warm offshelf waters. In fall, positive environmental PC2 loadings also extended into the deep waters of the Gulf of St. Lawrence. In both spring and fall, environmental PC3 differentiated waters with higher excess phosphate, salinity, chlorophyll, and oxygen (positive) from waters with higher excess silicate and temperature (negative), but the spatial distribution changed between spring and fall. Positive PC3 values occurred on the Newfoundland Shelf and Grand Bank in both seasons, but negative PC3 values were widespread in the Gulf of St. Lawrence in the spring but on the Scotian Shelf in the fall.

HERRING RELATIONSHIP TO PELAGIC HABITAT INDICATORS

Atlantic herring (*Clupea harengus*) are a logical first choice for exploring the application of pelagic ecosystem indices to inform ecosystem-based fisheries management. The commercially valuable herring are a key ecological link between lower and upper trophic levels in the NW Atlantic, and would thus be expected to be closely linked to physical and lower-trophic-level biological ecosystem drivers. This analysis focused on herring in the Maritimes Region, in the Bay of Fundy and on the Scotian Shelf (Northwest Atlantic Fisheries Organization [NAFO] divisions 4VWX).

The process of relating pelagic environmental indices to herring status can be broken down into three steps: identifying and calculating time series of herring status indices to include in the analysis, collating time series of pelagic ecosystem indices that might be related to herring status, and identifying potential indicators among those pelagic ecosystem indices that may predict herring status. All analyses and visualization were completed in R (R Core Team 2012).

HERRING INDICES

The indices for herring status chosen for analysis reflect herring recruitment, distribution, and condition, which were considered likely to respond to environmental drivers. The latter two are likely to respond rapidly, while recruitment would respond with a lag whose length depends on the age classes of the population represented by the recruitment index. Herring status indices and years for which they were calculated are provided in Table 1.

No Virtual Population Analysis estimates of recruitment have been published for the Southwest Nova complex for the period since 2006.Therefore, first-differenced estimates of spawning biomass from acoustic surveys of German Bank (GB) and Scots Bay (SB; Figure 7) conducted from commercial fishing vessels in 1999 to 2012 were used as a proxy for recruitment (Power et al. 2012, R. Singh, personal communication). Herring begin to recruit to these spawning grounds at age three as they mature (DFO 2011), so a three-year lag was used when comparing the recruitment index to other herring indices and to environmental indices. This index accounts neither for effects of natural and fishing mortality on the spawning biomass nor for variability in age at maturity, and acoustic survey estimates also suffer from other uncertainties (Power et al. 2012).

Annual indices of herring distribution were calculated using presence/absence data from the annual summer bottom trawl research vessel (RV) survey on the Scotian Shelf and in the Bay of Fundy from 1970 to 2012 (Table 1). Herring catch and tow information were extracted from the DFO Science Virtual Data Centre (VDC). Herring collected in strata not sampled consistently over the entire time series from 1970 to 2011 were omitted from distribution indices described here and from estimations of condition indices (below). Presence/absence was used because abundance information for herring from the RV surveys is considered unreliable due to sampling gear, fish processing protocols, and the potential effect of spatially and temporally variable predation pressure on herring catchability in bottom trawls. Distribution was characterized as percent positive tows (closely correlated to design-weighted area occupied, *sensu* Smedbol et al. 2002), decorrelation range, and spatial autocorrelation between nearest stations. Survey strata were divided into several subregions (Table 2, and outlined in Figure 7), including the outer Bay of Fundy (oBoF), Western Scotian Shelf (WSS), Central Scotian Shelf (CSS), ESS, and the Scotian Shelf as a whole (SS; here indicating the latter three subregions combined), based on previous work reporting independent patterns in herring condition for different areas (G. Melvin and R. Martin, unpublished data) and on proximity to AZMP sections. Strata in the inner Bay of Fundy and between the WSS and oBoF subregions were omitted from analyses because the groundfish surveys miss important herring habitat on the banks in these areas. Percent positive tow indices were calculated for each subregion and for the shelf as a whole, while decorrelation range (the x-intercept of a correlogram) and spatial autocorrelation at nearest stations (the correlogram value at the first lag) were calculated only for the whole Scotian Shelf starting in 1983, when there were consistently sufficient positive tows to support use of a spatial autocorrelation statistic. Correlograms were calculated with the correlog function in the ncf package for R (Bjornstad 2012). To isolate interannual variability in the distribution indices from pronounced trends evident in the time series, optimal ARIMA (AutoRegressive Integrated Moving Average) models were fitted with the auto.arima function in the forecast package for R (Hyndman et al. 2013) and the residuals were used as the distribution indices.

Condition (relative weight given length and other factors) was computed for herring caught in bottom trawls during summer RV surveys (1995-2011) for the same subregions delineated above for distribution indices, and for herring from commercial purse seine sets on GB (1974-2011) and SB (1976-2011; Table 2, Figure 7), resulting in six area-specific condition indices. Detail sample data, including individual lengths, weights, sex, and gonad maturity stage, were extracted from the herring schema on the St. Andrews Biological Station Oracle database.

The summer RV surveys provide information on summer feeding herring. Since percent positive stations and area occupied were highly correlated in preliminary analyses, condition indices calculated from RV surveys may be considered representative of the subregion for which they were computed (however, fish for detail data were not collected from all of the positive tows, so potential for bias exists). Detail data for summer RV surveys were merged with tow data from the VDC (see above). Condition indices for RV survey herring were based on adults of gonad maturity stages 3-5 (ripening through ripe but not yet spawning) and greater than 23 cm in length (length at 50% maturity for herring; Power et al. 2010). The upper length limit for each subregion was set such that each 10-mm length class contained at least 15 individuals. Stage 6 (spawning) herring were excluded due to the high variability seen in the weight-at-length relationships in this stage in preliminary analyses. Post-spawning stages were excluded in case of an interaction between pre-spawning condition and percent body weight invested in spawning.

GB and SB are important components of the 4VWX stock complex where spawning herring have been fished with a non-selective gear type (purse seine) over a long time series with few gaps. Since herring are considered to exhibit spawning site fidelity (Stephenson et al. 2009), condition information for these areas is directly relevant to a particular stock component. To increase the likelihood that herring included in calculation of the spawning-ground-specific condition indices belonged to the local stock component, the indices were based on adults at gonad maturity stage 5 and greater than 23 cm in length, with a catch date within peak spawning months for the area (July to September for SB, August through October for GB). Upper length limits were determined as for the RV survey condition indices.

For each of the six area-specific condition indices (four from RV surveys on the Scotian Shelf and two from commercial tows on GB and SB), year effects on condition were estimated using a linear mixed effects model fit with the nlme package in R (Pinheiro et al. 2012). Ln-transformed weight was modeled as a function of ln-transformed length, gonad maturity stage (for RV survey indices), sex, and year, with year used as a factor and tow included as a random effect with random intercept (to account for correlation among herring sampled simultaneously). This approach eliminates concerns about condition factor (as Fulton's K) changing with length (Bolger and Connolly 1989, Cone 1989, Springer and Murphy 1990). Log-transformed length was first centered on zero to avoid model fitting dependency between the intercept and coefficients for length. The full model for each index included interactions among length, maturity, and sex. Exploratory data analysis revealed that ln-transformed weight varied non-linearly with ln-transformed length, so length was modeled as a 3rd degree polynomial. Possible heterogeneity of variance with maturity stage was diagnosed, so a term allowing variance to vary with gonad maturity stage was included in models for RV survey data. Variance also appeared to be heterogeneous with year, but models specifying independent variances by year caused a crash during optimization. Data points corresponding to standardized residuals of the full model outside limits for which one representative point would be expected given sample size were classified as outliers and omitted from further model fitting. A final model corresponding to each condition index was selected based on stepwise backward selection using Akaike Information Criterion (AIC), a relatively aggressive model selection criterion, to ensure that any potential influence of sampled lengths, sexes and maturity stages and interactions among these were accounted for when estimating year effects. The inclusion of the random effect was assessed based on comparing full models with and without it that were fitted using restricted maximum likelihood. Fixed effects were chosen based on comparisons of models fitted using maximum likelihood (Zuur et al. 2009). Selection of fixed effects used the stepAIC function in the package MASS for R (Venables and Ripley 2002).

PELAGIC ENVIRONMENT METRICS

A range of metrics representing the state of the pelagic environment were considered as potential drivers of the herring indices. These included local scores for the environmental and zooplankton PCAs described above, climate metrics, spring bloom characteristics from satellite ocean color data, environmental data collected on the summer RV surveys, environmental and zooplankton metrics from Scotian Shelf AZMP lines, and local and regional ocean temperature anomalies described in Hebert et al. (2012). All pelagic environment metrics and time spans are provided in Table 1.

Climate metrics included the North Atlantic Oscillation index, St. Lawrence River runoff (measured at Québec and summed January through May), Labrador Current volume transport across NE Track 191 (Han 2006, Han and Li 2008), shown to be related to Gulf of Maine processes by Wanamaker et al. (2007) (data accessed from the climate index page of the AZMP website on 19 February 2013), and maximum ice volume for the Gulf of St. Lawrence and Scotian Shelf combined (Galbraith et al. 2012). Lagged climate metrics were also explored, since other work has shown lags of one to four years in propagation of upstream perturbations to the Scotian Shelf and Gulf of Maine (e.g. Pershing et al. 2010).

The environmental and zooplankton PC scores used in the herring analyses were generated using an earlier iteration of the analysis presented above. There were only minor differences between the two iterations, and the overall relationships among variables identified were the same. The PC scores were averaged over Maritimes Region sections and across each Scotian Shelf section for each year of sampling, 1999-2011.

Standardized station anomalies for specific variables from AZMP surveys were also averaged by section and across all Scotian Shelf sections. Variables included spring abundances of *Calanus finmarchicus* (sum of all copepodite stages) and *Pseudocalanus* spp. (mainly late copepodites and adults), fall abundances of warm offshore species (*Clausocalanus* spp., *Mecynocera clausi*, and *Pleuromamma borealis*), and both spring and fall values for zooplankton biomass, mean temperature in the top 50 m (T0_50), mean salinity in the top 50 m (S0_50), stratification index (density difference between the 5 and 50 m; STRAT), near-bottom temperature (T_NB), near-bottom salinity (S_NB), and area of the CIL.

Quantitative spring bloom characteristics based on satellite ocean color data from SeaWiFS and MODIS include bloom start date, duration, and magnitude for the WSS, CSS, and ESS satellite statistical boxes (Johnson et al. 2013). Spring bloom metrics from SeaWiFS data for reliable instrument years (1998-2007) were combined with those from MODIS data (2008-2012) to complete the time series overlapping with the AZMP surveys. Data exploration of overlapping years between the two instruments (2003-2007) showed a strong relationship close to 1:1 for bloom start date between the instruments, and a weaker relationship between instruments with greater year to year variability for bloom duration and magnitude. No correction factor was used in combining the time series from the two instruments for any of the three metrics due to insufficient information.

Environmental data collected on the RV summer groundfish surveys were included to investigate whether closer relationships with herring indices from RV surveys could be found with variables measured concurrently, including bottle data for chlorophyll and temperature and salinity profiles. Chlorophyll bottle data were collected at consistent depths starting in 2002, and integrated chlorophyll over the top 50 m for 2002-2012 was calculated per station, averaged by groundfish survey stratum, and these were averaged within polygons corresponding to roughly the same subregions used for the herring indices (Figure 7, Table 2). Hydrographic variables were interpolated onto a 0.2° by 0.2° latitude-longitude grid using an objective analysis procedure known as optimal estimation (Petrie et al. 1996, Hebert et al. 2013). Spatial averages

of hydrographic variables were calculated for the regions described in Table 2 using the gridded data.

APPROACH TO IDENTIFYING POTENTIAL INDICATORS

The time series of most pelagic environment metrics were too short to allow robust multivariate analysis of relationships between pelagic environment metrics and herring indices to search for and develop potential indicators. To visualize patterns in relationships between pelagic environment metrics and herring indices and identify potential indicators, correlation matrices for herring indices and corresponding environment metrics were calculated using Kendall's tau (a rank-based measure) and the herring-environment correlation coefficients were plotted as corrgrams (Murdoch and Chow 1996, Friendly 2002), using the R package corrplot (Wei 2013). In addition, a corrgram was plotted for the portion of the correlation matrix relating herring indices with each other to gain an overview of how they covary.

To isolate the ability to predict extreme values in the herring indices (e.g. years of exceptionally good or bad condition), each index and environment metric was converted to an ordinal scale with three possible values according to whether original values were in the bottom quartile, mid two quartiles, or top quartile of values for that index. These ordered factor indices were used to calculate correlation matrices with Kendall's tau and the results plotted as corrgrams.

The pelagic environment metrics can be classified as predictive, concurrent, or retrospective, based on the timing of their availability within each year relative to the collection of data for the herring indices. These classifications are delineated in the resulting corrgrams to emphasize the strength of relationships of predictive metrics with herring indices relative to concurrent and retrospective metrics.

Herring indices were related to a suite of geographically proximate environmental metrics where local measurements were available in addition to broad-scale regional metrics. Thus, herring indices for the ESS were related to time series for the Louisbourg Line for PCA scores and individual zooplankton and environment metrics, ESS satellite spring bloom characteristics, and annual temperature anomalies for surface and 50 m at Misaine Bank and for bottom temperature in 4Vs. Herring indices for CSS were related to time series for the Halifax Line, CSS satellite spring bloom characteristics, and annual temperature anomalies for surface and 50 m at Emerald Basin and for bottom temperature in 4W. Herring indices for WSS were related to time series for the Browns Bank Line, WSS satellite spring bloom characteristics, and annual temperature anomalies for surface and 50 m at Georges Basin and for bottom temperature in 4X. The latter set of metrics were also related to GB, SB, and oBoF herring indices, except temperature anomalies at Prince 5 at 0 m and 90 m and at Lurcher Shoal at 0 m and 50 m were substituted for Georges Basin anomalies.

CORRELATIONS AMONG HERRING INDICES

In fitting linear mixed effects model to herring condition data, a random intercept term for tow was retained for all models. All models included length, year effect, sex, gonad maturity stage (where multiple stages were included), and interaction between maturity and length (Table 3). Interactions between sex and length were retained in three of the seven models and between sex and maturity in four of the five models in which maturity stage was included. The full model was retained for WSS herring condition. Sample sizes and numbers of groups included in models ranged from 622 fish in 130 tows to 8295 fish in 924 tows.

The resulting herring index time series for recruitment, distribution, and condition are presented in Figure 8. The condition indices in particular showed synchrony in "good" and "bad" years among areas. The patterns among herring indices are further illustrated by a corrgram for all indices plus straight biomass at GB and SB and differenced biomass on those two spawning

grounds at lag zero (Figure 9). Biomass and zero-lag differenced biomass were included in the corrgram to examine how condition on the spawning grounds, recruitment, and percent positive tows in nearby areas vary with abundance, and how differenced biomass varies with condition in the same area.

Condition was strongly positively correlated ($p<0.01$) among subregions on the Scotian Shelf, less so ($p<0.1$) with SB, and still less with GB and oBoF. Percent positive tows were correlated among the CSS, the WSS, and the shelf as a whole. Percent positive tows on the ESS appeared to be independent of the other Scotian Shelf areas but strongly negatively related to condition across the shelf ($p<0.01$). Condition on the ESS was also the least well correlated with condition in other Scotian Shelf areas.

Differenced biomass did not appear to be driven by condition at GB in the same year, and was only weakly correlated at SB ($p>0.1$). No other clear relationships emerged between acoustic biomass estimates for a given year and distribution, recruitment, or condition.

RELATIONSHIPS BETWEEN HERRING INDICES AND POTENTIAL PELAGIC ECOSYSTEM INDICATORS

The corrgrams for herring indices with environmental metrics show some consistent patterns, although the number of significant correlations observed in each case was similar to the approximately 10% that would be expected to produce a $p<0.1$ by random chance alone (figures 10-11). Corrgrams using ordered factors appeared to increase the strength of correlations and possibly the power of detecting relationships, but the calculations of probability did not correct for ties (Figure 12-13). The interpretation presented here focuses on consistent correlations among similar types of indices and those for which a clear mechanism for a driver-response relationship can be posited. Emphasis is placed on predictive relationships, since those would be most relevant to developing useful indicators of likely future herring status.

Herring condition on the CSS, WSS and SS were weakly correlated with spring environmental PC2 and PC3 and with metrics associated with colder temperatures, including ice volume and deep-water temperature (Figure 10a). Positive spring environmental PC2 was associated with higher CIL thickness, excess silicate, and oxygen, and lower temperature and salinity, and positive values of PC2 were almost ubiquitous in the Gulf of St. Lawrence. Positive PC3 was associated with higher chlorophyll concentrations, cool temperature, and weaker stratification. The ESS distribution index (percent positive ESS) was negatively correlated with spring environmental PC2 and PC3 and with ice volume, consistent with its negative correlation to SS condition.

Correlations between SS herring condition and cool temperatures were enhanced in the ordered factors corrgrams, but the correlation between condition and environmental PC3 disappeared (Figure 12a). There were positive correlations between herring condition and *Pseudocalanus* spp. and *C. finmarchicus* abundance on the SS in the ordered factors corrgram, as well as negative correlations of SS herring condition with rivsum and positive correlations with rivsum lagged by one year. Overall, good herring condition was associated with years of cooler temperatures, more ice in the Gulf of St. Lawrence, and environmental conditions similar to the Gulf of St. Lawrence). Positive correlations between condition in areas of the SS and dominant copepod abundance and relationships to NAO and rivsum emerged in the ordered factors corrgram.

Climate indices also showed some consistent relationships with herring indices. NAO at zero lag is consistently positively related to herring condition across areas, but lag 2 is positively related to SS condition while lag 3 is negatively related to condition in the eastern Gulf of Maine region. A similar inverse relationship between the SS and eastern Gulf of Maine region exists for maximum ice volume in the Gulf of St Lawrence and Scotian Shelf (positive at lag zero with SS,

negative at lag one with SW region). The lags expected for climate indices are two years for NAO to the shelf, and three to four years to the Gulf of Maine (Head and Sameoto 2007, Pershing et al. 2010, Wanamaker et al. 2007).

Among concurrent and retrospective metrics, SS, WSS, and CSS herring condition had positive correlations with fall environmental PC1, negative correlations with fall environmental PC2, and a positive correlation between SS-wide condition and fall environmental PC3 (Figure 10b). Correlation SS, the spatial autocorrelation between nearest stations, also had positive correlations with the fall environmental PC1 and PC3 and a negative correlation to PC2, in addition to a negative correlation with fall zooplankton PC1. Percent positive ESS was positively correlated with fall environmental PC2 and negatively correlated with fall environmental PC3. The relationships between SS herring condition and fall environmental PCs held, for the most part, in the ordered factors corrgrams (Figure 12b). The fall environment PC1 was associated with high shallow and deep nutrient concentrations and low temperature, with strong positive values in the deep waters of the NW Gulf of St. Lawrence. Negative fall environment PC2 values were associated with high excess silicate, excess phosphate and surface oxygen concentration, lower deep-water nitrate inventories, and lower salinity. The most negative PC2 values were observed on the inshore Grand Bank and shallow southern Gulf of St. Lawrence. Thus, good herring condition seems to be associated with the water properties similar to the Gulf of St. Lawrence and inshore shelf in fall.

There were few consistent patterns in correlations of eastern Gulf of Maine herring condition, distribution, and recruitment metrics with environmental metrics (Figures 11 and 13). Only in the predictive ordered factors corrgram were there more than the expected number of correlations with $p<0.1$ (Figure 13a). GB herring condition was positively correlated with Browns Bank *C. finmarchicus* abundance and spring zooplankton PC2, which was most strongly associated with *M. lucens*, Euphausiids, and *C. finmarchicus*, and negatively correlated with one- and two-year lagged ice volume. GB herring recruitment (lag 3) was also correlated with Browns Bank *C. finmarchicus* abundance. In contrast, oBoF herring condition and distribution (percent positive) were negatively correlated with Prince-5 *C. finmarchicus* but positively correlated with Prince-5 and Browns Bank *Pseudocalanus* spp. SB herring condition was negatively correlated with spring environment PC1, associated with high nutrient, offshore water, but SB recruitment (lag 3) had the opposite relationship to spring environment PC1 and was also positively correlated with spring zooplankton PC1, associated with deep water species.

DISCUSSION

The influences of large-scale and regional processes on the shelf system were evident in the patterns that emerged from the multivariate analyses. Ocean properties often vary non-independently, for example, temperature and salinity are not independent variables in water masses isolated from the surface, and species associations are a typical element of plankton community variability. PCA was used here to characterize the dominant joint patterns of variability among variables, their spatial pattern and interannual relationships to herring population metrics.

The strong shelf-slope zooplankton community gradient identified by PC1 has also been observed in previous studies (Tremblay and Roff 1983, Johnson et al. 2011). The species loadings on PC1 in both seasons suggested that the gradient reflected both the community transition across the strong environmental gradient at the shelf break and species' life history and behavioural requirements for shallow or deep water. Species loadings and regional patterns in zooplankton PC2 in fall reflected the distributions of warm-water and cool-water shelf species, and the fall PC2 was associated with an along-shelf pattern of spatial variability, likely related to an along-shelf gradient in temperature. In spring, PC2 may have been related to regional differences in seasonal community development. The shift in PC2 loadings between spring and

fall appears to reflect annual community succession, as warm-water species become more abundant in summer and fall. PC2 appears to be sensitive to zooplankton responses to the annual temperature cycle, in addition to spatial differences in temperature. Zooplankton PC3 reflected differences in the communities in the Gulf of St. Lawrence and outer shelf in both seasons.

The spatial variability in the environment PC1 differed from the patterns identified in the zooplankton PCA and reflected high nutrient concentrations in both the northwest Gulf of St. Lawrence, driven by nutrient regeneration and deep inflow through the Laurentian Channel (Savenkoff et al. 1996), and on the Newfoundland Slope and offshore waters, likely influenced by high nutrient, poleward flowing North Atlantic Current water east and northeast of the Grand Bank (Fratantoni and McCartney 2010, Maillet et al. 2005). The number of nutrient variables and their strong covariance probably contributed to the dominance of nutrient patterns in the environmental PCA. Cross-shelf variability was evident in environmental PC2 both in spring and fall, but the dominant factors driving the pattern differed in spring (temperature, salinity, CIL thickness) and fall (excess nutrients, salinity, and deep-water nutrients). Regional differences were evident in environmental PC3, with a shift from the strongest differences between the Newfoundland Shelf and Gulf of St. Lawrence in spring and to the Newfoundland Shelf and the Scotian Shelf in fall.

Multivariate scores, such as the PC score reported here, can be considered indicators of the dominant modes of large-scale spatial variability in the pelagic environment and the zooplankton communities (e.g. Hare and Kane 2012, Keister and Peterson 2003). Both spatial and interannual variability were included in the underlying data, but the coherent regional spatial pattern evident in the PC scores highlighted the strong influence of large-scale spatial processes. Interannual variability in PC scores can be interpreted to represent shifts in biogeographic zones or changes in the relative influence of different water sources in an area. Changes in zooplankton PC1 and environmental PC2 indicate a change in cross-shelf transport of zooplankton or water. Shifts in zooplankton PC2 may indicate an along-shore shift in habitat for warm-water and cold water zooplankton communities or changes in community seasonal succession. Changes in zooplankton PC3 or environmental PC3 could be interpreted as a change in the influence of a water sources on a given area, for example the influence of Gulf of St. Lawrence outflow on the Scotian Shelf. This analysis is a first effort to use multivariate analysis to develop indicators of large-scale changes in pelagic habitat at the scale of the Canadian NW Atlantic shelf system. While the dominant modes of variability identified in the analysis appear to be robust, changes in the specific choices of variables and transformations used in the subsequent iterations may alter some details of the results.

Herring were chosen for comparison with the PC scores and other environmental metrics because variability in the physical environment and zooplankton prey availability can influence their recruitment and condition (Winters and Wheeler 1987, Möllmann et al. 2005). Overall, the herring metrics had few significant correlations to one another. The strongest set of correlations were among the Scotian Shelf condition metrics, suggesting regional-scale drivers of condition on the Scotian Shelf, while the mostly uncorrelated eastern Gulf of Maine condition metrics suggested that the factors controlling condition could be different for these groups. These patterns were consistent with the phase of the life cycle at which herring were sampled in these two areas. Herring demonstrate fidelity to individual spawning grounds, but stocks have annual migrations and can share common feeding and overwintering areas (Stephenson et al. 2009). The eastern Gulf of Maine herring were sampled on their spawning grounds, and the groups are different stocks whose condition reflects feeding in different areas (Stobo 1982). On the other hand, the Scotian Shelf herring were sampled in their feeding areas and represent a mixture of stocks. The negative correlation between percent positive tows on the ESS and condition in all areas of the Scotian Shelf suggests that the environmental or population factors that promote

good herring condition in this area may be associated with a shift in herring distribution to the west.

The negative correlation between Scotian Shelf herring condition and distribution on the ESS may reflect density-dependence in growth, as has been observed by Winters and Wheeler (1994). Although herring abundance data were not included in this analysis, the period when condition data were available was a period of high herring abundance during which herring growth may have been limited by food availability (Frank et al. 2011). Expansion of herring distributions has also been observed when population abundance increases (Melvin and Stephenson 2007), consistent with the interpretation that condition may have been lower due to density-dependence.

The correlations between Scotian Shelf herring condition and multivariate and individual environmental metrics suggested that condition was better when waters were colder and more like the Gulf of St. Lawrence, suggesting that better condition may be associated with more outflow from the Gulf of St. Lawrence onto the Scotian Shelf, along with more limited distribution on the ESS. The mechanism underlying this relationship is not clear at this time, but Scotian Shelf primary and secondary production may be more efficient when there is more outflow of cold, high-nutrient waters from the Gulf of St. Lawrence. Although the power of the analysis was low due to the limited length of the time series, the relationships identified in the analysis implied hypotheses about environmental drivers that may be testable using the longer physical time series.

Among the lower trophic level indices, *Pseudocalanus* spp. showed up repeatedly as more or less strongly positively correlated with condition on the Scotian Shelf, and the relationships for both *Pseudocalanus* spp. and *C. finmarchicus* were accentuated in the Scotian Shelf ordered factors corrgrams. *Pseudocalanus* spp. has been shown to be an important driver of herring condition in the Baltic Sea (Möllmann et al. 2005). The relationships between these taxa and the herring indices may be responsible for the patterns observed between herring indices and the zooplankton PCs: *Pseudocalanus* spp. had a negative loading on PC1, which was negatively correlated with condition on the Shelf and in the Bay of Fundy, while *C. finmarchicus* had a positive loading on PC2, which was positively related to condition, particularly at GB.

The eastern Gulf of Maine analysis identified some potentially informative relationships, but the herring metrics appear to be responsive to pelagic habitat metrics at a smaller scale than on the Scotian Shelf and at locations not well characterized by the environmental analysis described here.

CONCLUSIONS

Dominant patterns of large-scale variability in zooplankton communities and the pelagic environment were characterized by PCA. Correlations between herring condition, distribution, and recruitment metrics and the environment and zooplankton PC scores and other, single-variable pelagic habitat metrics were fairly weak, in part because of the short length of the time series used in the analysis. However, variability in outflow from the Gulf of St. Lawrence appeared to be important to Scotian Shelf herring condition and distribution. Greater coherence in herring metrics on the feeding grounds than on spawning grounds may be due to stock mixing and more immediate response to local environment.

Emphasis for further work should be placed on several key elements that deserve greater attention. First, further acquisition and exploration of longer time series, particularly for zooplankton in the Gulf of Maine where little information was available for this analysis, may provide stronger support or new ideas for possible indicators. National Oceanographic and Atmospheric Administration (NOAA) sampling programs in the Gulf of Maine may prove useful for this purpose. Another useful source of longer time series data may be temperature

scorecard data from only spring and summer rather than averaged for the year as presented in Galbraith et al. (2012). Longer time series of more defensible recruitment indices (e.g. from VPA) should be used for future work, when they become available. Second, variability of condition among individual fish within years should be investigated, since herring may experience more variable foraging success in some years than others, which may provide additional information to the mean condition per year examined here. Finally, several avenues could be explored for increasing the power of the analysis possible with the data currently available, such as taking a nested modeling approach for similarly behaving herring indices, combining indices without adding new model parameters, (such as by summing standard anomalies, *sensu* Galbraith et al. 2012), and removing the influence of a common driver to find other common drivers that explain residual variance. Emphasis should be placed on developing the means to predict exceptionally poor years for recruitment and condition to support adaptive ecosystem-based management. In addition, more localized PCAs (e.g. for the Scotian Shelf) may help to highlight the major sources of variation for target areas that are not sensitive to large-scale variability.

ACKNOWLEDGEMENTS

The authors thank Gary Melvin, Kes Morton, and Christa Waters for helpful discussions about design of the analysis, Gillian Fung and Roger Pettipas for assistance with data assembly, Andrew Cogswell for assistance in formatting the report, and the scientists, staff, ships' officers and crew involved in collecting the data used in the analysis. The authors also thank Michel Mitchell and Jeffrey Runge for reviews of the manuscript.

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TABLES

Table 1. Herring and pelagic environment indices and years in time series. Geographic areas include Browns Bank section (BBL), Central Scotian Shelf (CSS), Eastern Scotian Shelf (ESS), German Bank (GB), Gulf of St. Lawrence (GSL), Halifax section (HL), Louisbourg section (LL), outer Bay of Fundy (oBoF), Prince-5 (P5), Scots Bay (SB), Scotian Shelf (SS), and Western Scotian Shelf (WSS).

Index	Years sampled (missing)
Herring	
Recruitment	
Differenced acoustic biomass, GB, lag 3	1997-2009
Differenced acoustic biomass, SB, lag 3	1997-2009
Distribution	
Autocorrelation at first lag	1983-2012
Range (decorrelation length scale)	1983-2012
Percent positive for SS, ESS, CSS, WSS, oBoF	1970-2012
Condition	
Condition for SS, ESS, CSS, WSS, oBoF	1995-2011
Condition, GB	1974-2011 (1988)
Condition, SB	1976-2011 (1982-1986)
Environment	
Climate	
North Atlantic Oscillation (NAO) index	1970-2011
St. Lawrence River runoff at Québec, Jan. - May (rivsum)	1970-2011
Labrador Current volume transport (NE Track 191) (LCVT)	1993-2010
Maximum ice volume (ice.vol) for GSL+SS	1970-2012
Hydrographic and Bottle	
Annual temperature anomalies (summed and indiv.)	1970-2012
Temperature, salinity, stratification, AZMP sections, spring	1999-2011 (2002)
Temperature, salinity, stratification, HL section, SS, fall	1999-2011 (2003)
Temperature, salinity, stratification, BBL and LL section, fall	1999-2011 (2003, 2010)
Environment PC scores, spring (epc.sp)	1999-2011 (2002, 2003 for BBL and HL)
Environment PC scores, fall (epc.fa)	1999-2011 (HL: 2003, 2000; LL: 2008 and 2010)
Summer RV hydrography	1999-2011
Summer RV integrated chlorophyll	2002-2012
Satellite Chlorophyll	
Bloom start date, amplitude (amp), duration (dur)	1998-2007 (SeaWiFS), 2008-2012(MODIS)
Zooplankton	
AZMP HL section and SS mean, spring and fall	1999-2012
AZMP BBL and LL section, spring and fall	1999-2012 (missing 1-3 years)
P5 (Bay of Fundy), spring and fall	1999-2012
Zooplankton PC scores, spring (zpc.sp)	1999-2011 (2002)
Zooplankton PC scores, fall (zpc.fa)	1999-2011 (2010 for BBL and LL)

Table 2. Index areas as defined by strata or corresponding geographic bounding boxes.

Subregion	Strata or bounding box coordinates
Outer Bay of Fundy	490:493
Western Scotian Shelf	474:478,480:483
Central Scotian Shelf	460:466,470:473
Eastern Scotian Shelf	443:459
Scotian Shelf	443:459,460:466,470:473,474:478,480:483
German Bank	lon = -66.83, -66.83, -66.08, -66.08; lat = 43, 43.75, 43.75, 43
Scots Bay	lon = -65.4, -65.4, -64.25, -64.25; lat = 44.7, 45.4, 45.4, 45

Table 3. Models for herring condition indices, with Akaike Information Criterion (AIC) provided for final model and change in AIC resulting if further terms dropped. Index areas include Scotian Shelf (SS), Eastern Scotian Shelf (ESS), Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), outer Bay of Fundy (oBoF), German Bank (GB), and Scots Bay (SB). Poly(ln(LEN)) indicates a third-degree polynomial function of ln-transformed length, M is gonad maturity stage, S is sex, and Y is year (incorporated as a factor). All interacting terms include their components and an intercept as independent terms in the model.

Index	Final model	Next terms to drop	AIC
SS	ln(W) ~ poly(ln(L),3)*M + poly(ln(L),3)*S + M*S + Y	n/a	-20137
		M*S	-20107
		poly(ln(L),3)*S	-20105
		poly(ln(L), 3)*M	-20090
		Y	-19792
ESS	ln(W) ~ poly(ln(L),3)*M + M*S + Y	n/a	-5013.1
		poly(ln(L),3)*M	-5013.1
		M*S	-5002.5
		Y	-4989.3
CSS	ln(W) ~ poly(ln(L),3)*M + poly(ln(L),3)*S + M*S + Y	n/a	-9605.4
		M*S	-9602.3
		poly(ln(L),3)*S	-9585.6
		poly(ln(L),3)*M	-9571.5
		Y	-9390.1
WSS	ln(W) ~ poly(ln(L),3)*M*S + Y	n/a	-5551.1
		poly(ln(L),3)*M*S	-5549.9
		Y	-5406.6
oBoF	ln(W) ~ poly(ln(L),3)*M + S + Y	n/a	-1452.3
		S	-1452.1
		poly(ln(L),3)*M	-1449.7
		Y	-1433.4
GB[1]	ln(W) ~ poly(ln(L),3) + S + Y	n/a	-10164
		Y	-10104
		S	-10016
		poly(ln(L),3	1516
SB[1]	ln(W) ~ poly(ln(L),3) + S + Y	n/a	-9210.1
		S	-9170.6
		Y	-8967.1
		poly(ln(L),3)	1591.1

[1] GB and SB have no term for maturity stage because only one stage is included in the data for the spawning grounds.

FIGURES

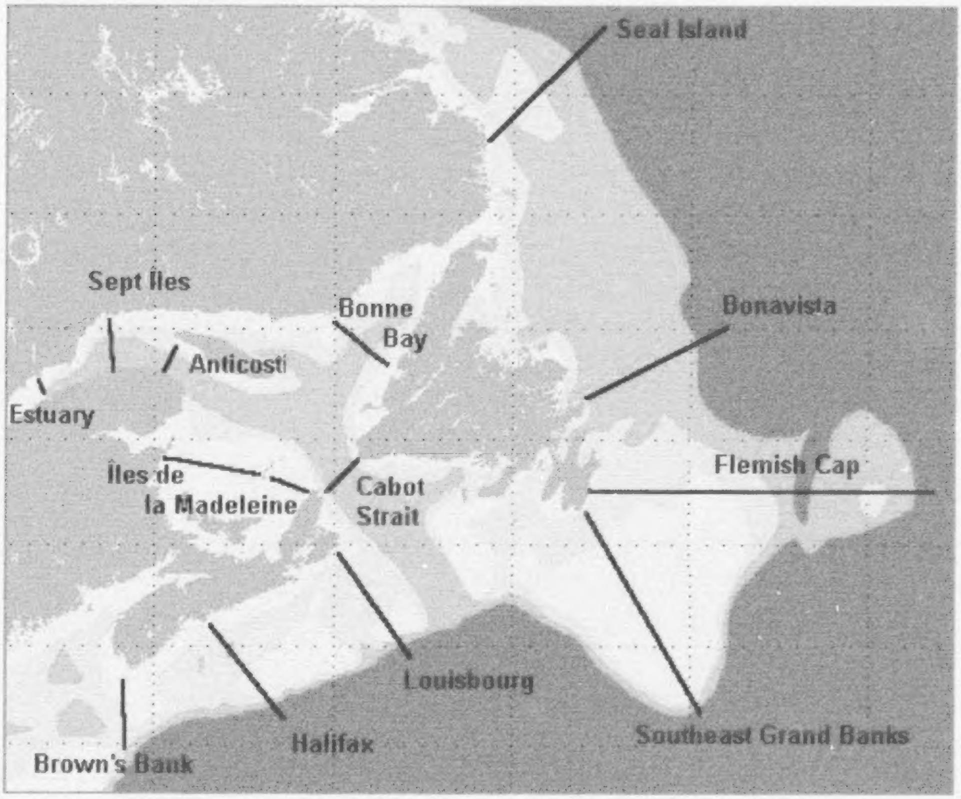


Figure 1. Map of AZMP core sampling sections.

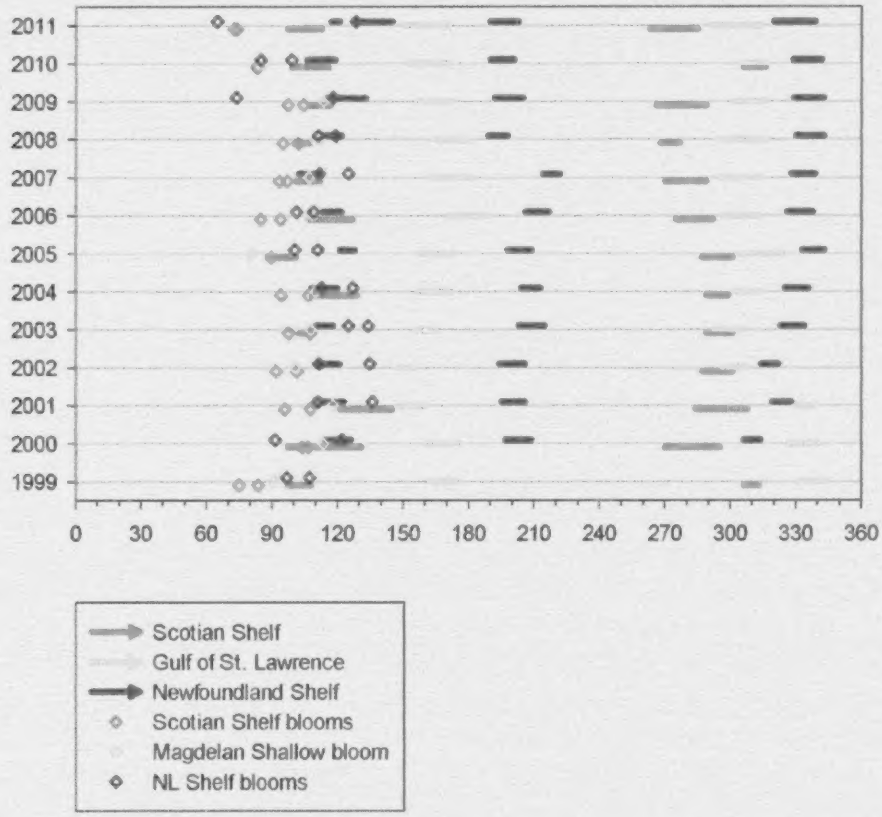


Figure 2. Timing of sampling on cross-shelf section surveys in the three AZMP regions. Spring bloom timing is noted as open diamonds.

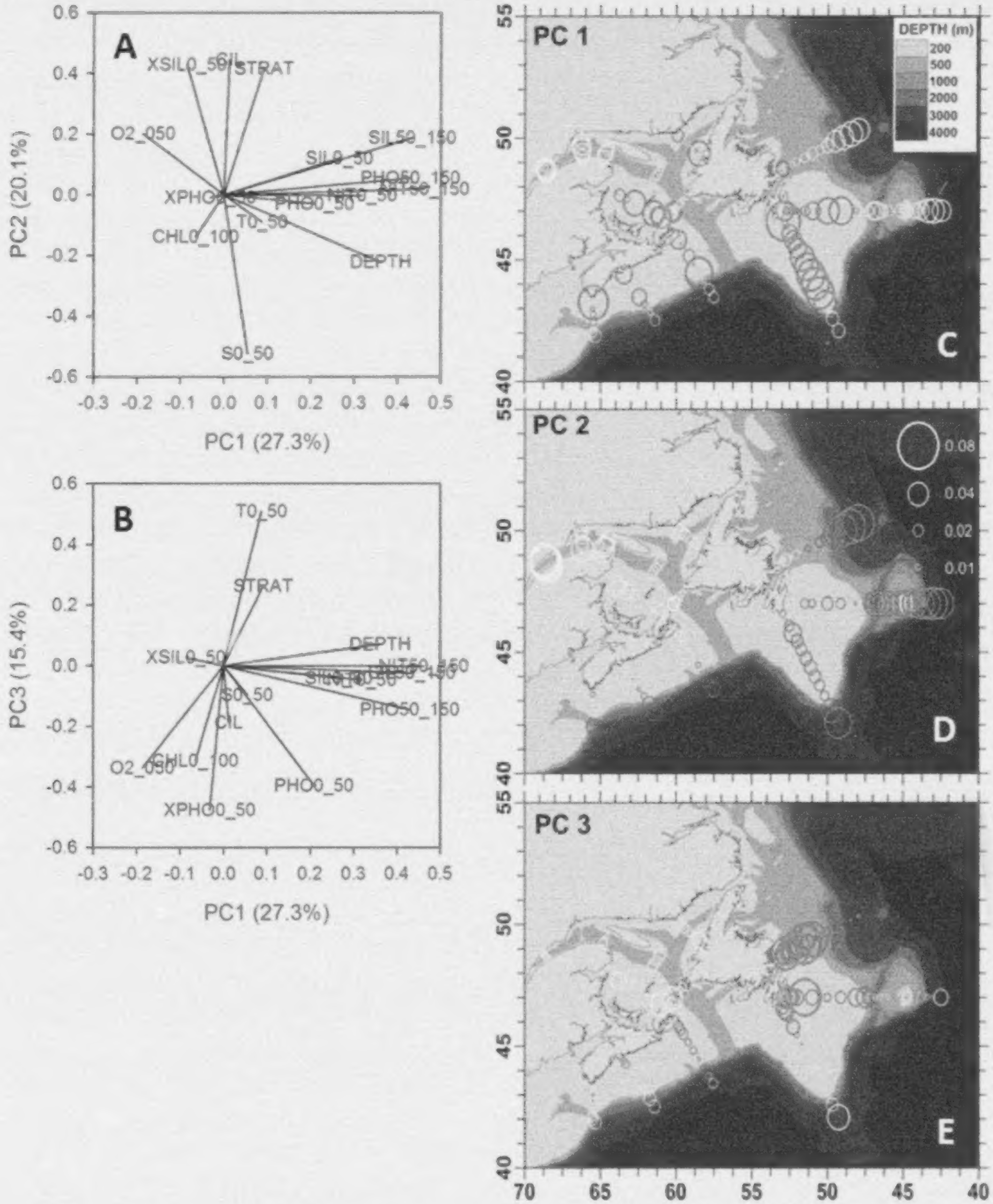


Figure 3. Patterns of variation in environmental variables from the spring oceanographic surveys based on the first three axes (PC1 – PC3) derived from a PCA. Loadings on each PC are represented in panels A and B, and the percentage of variation associated with each axis appears in brackets next to the title. Spatial distributions of the average spring principal component scores (PC1 – C; PC2 – D; PC3 – E) are represented for each sampling site (red – negative; white – positive; expanding symbol legend in yellow in the middle).

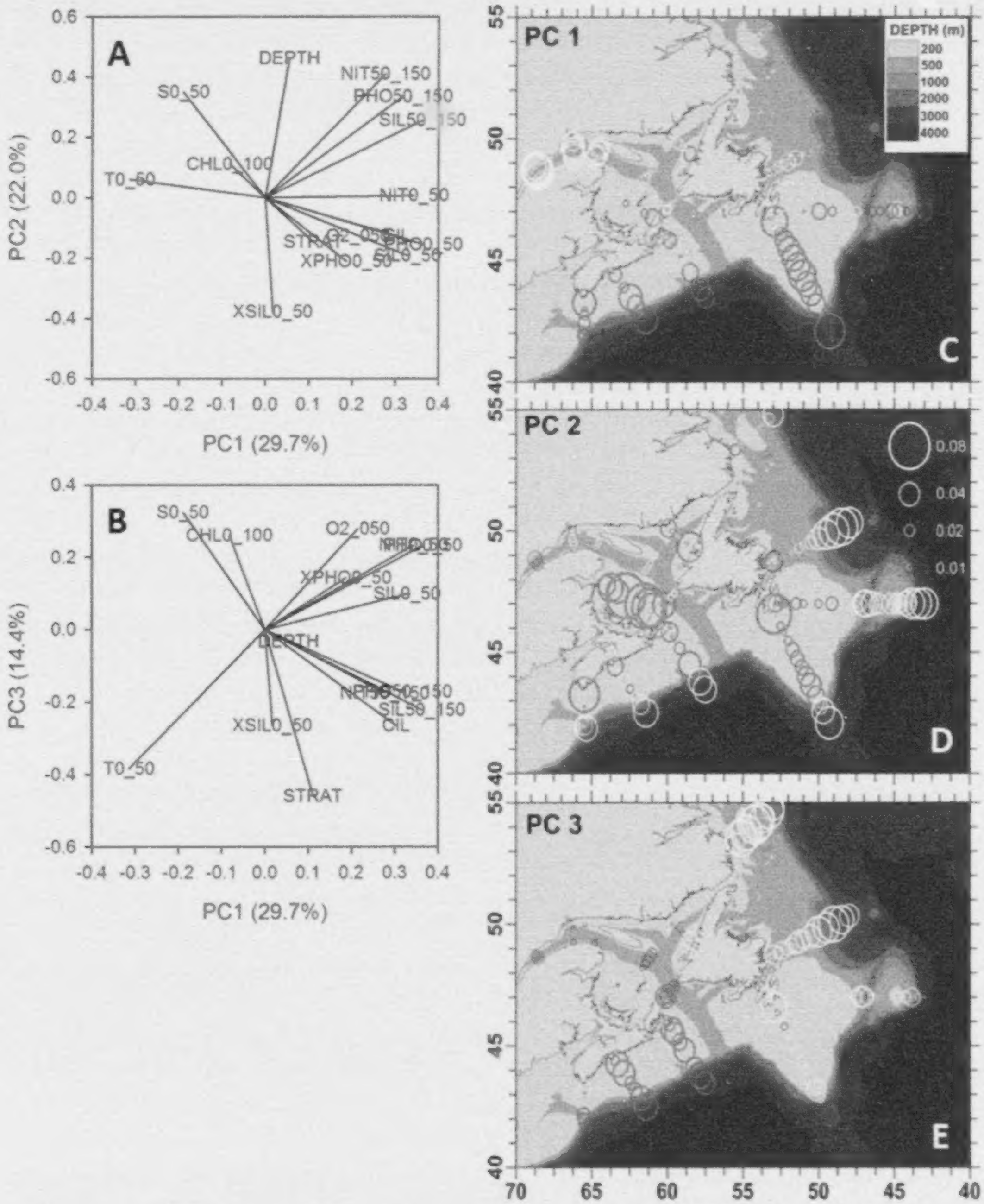


Figure 4. Patterns of variation in environmental variables from the fall oceanographic surveys based on the first three axes (PC1 – PC3) derived from a PCA. Loadings on each PC are represented in panels A and B, and the percentage of variation associated with each axis appears in brackets next to the title. Spatial distributions of the average fall principal component scores (PC1 – C; PC2 – D; PC3 – E) are represented for each sampling site (red – negative; white – positive; expanding symbol legend in yellow in the middle panel).

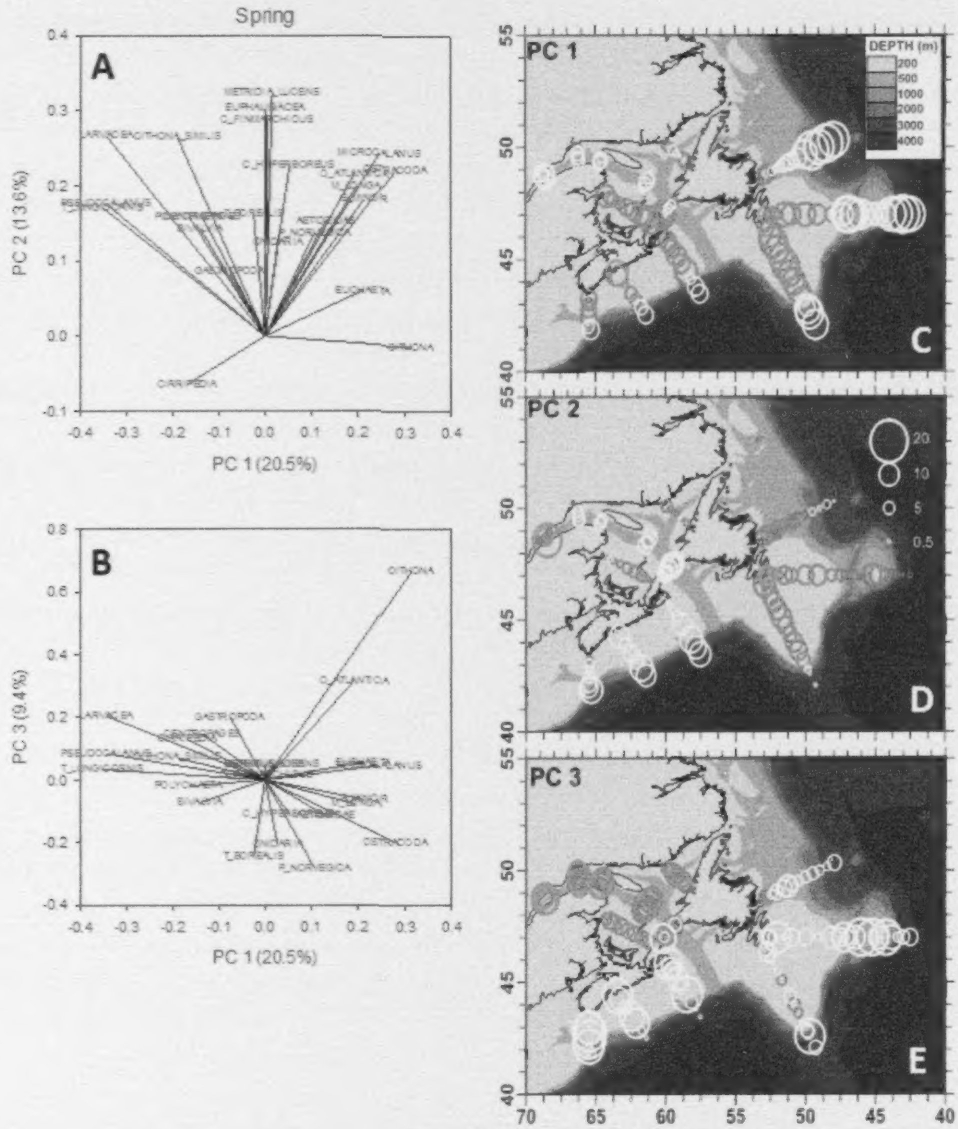


Figure 5. Principal component plot of species abundance loadings on the first three axes of the analysis of the spring dataset (A, B). Spatial distribution of the average spring principal component scores (PC1 – C; PC2 – D; PC3 – E) for each sampling site (red – negative; white – positive; expanding symbol legend in yellow in the middle panel).

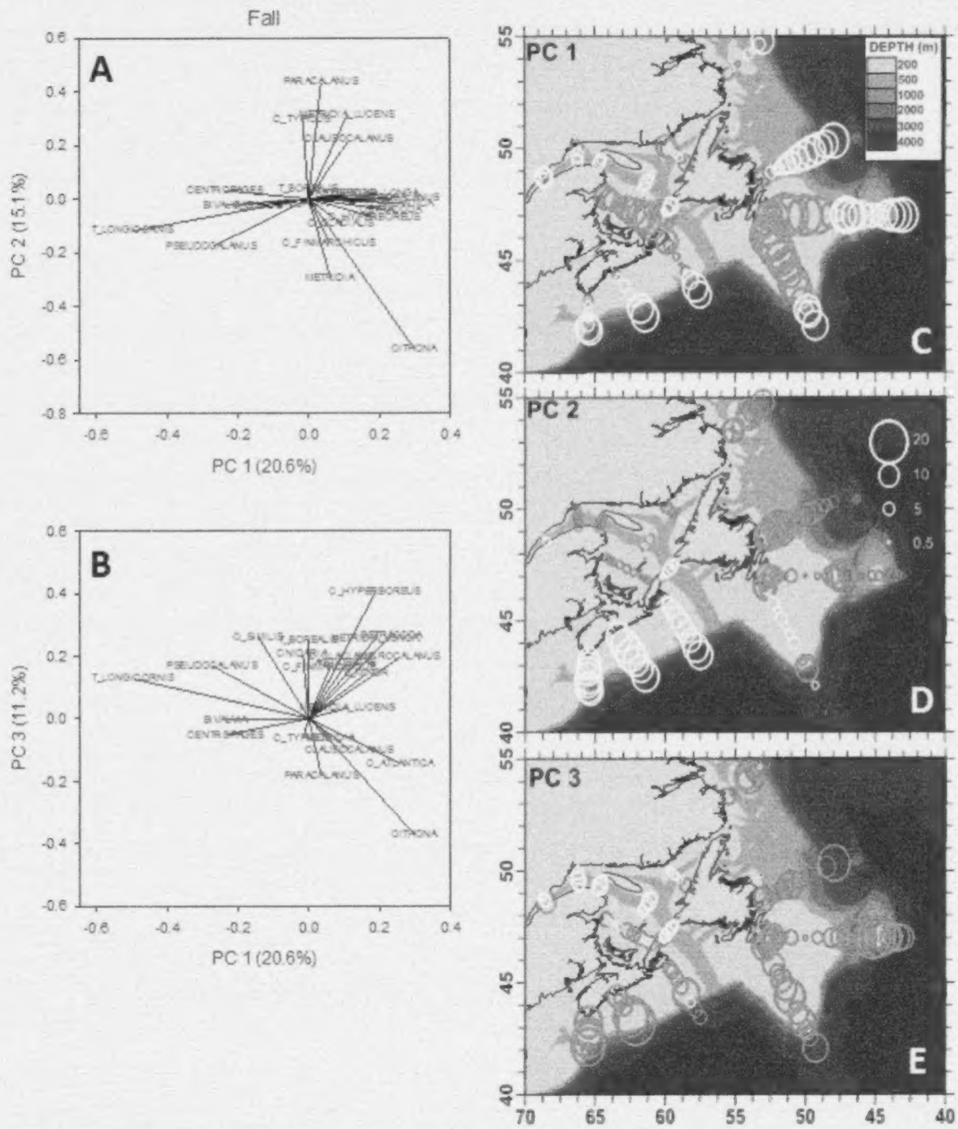


Figure 6. Principal component plot of species abundance loadings on the first three axes of the analysis of the fall dataset (A, B). Spatial distribution of the average fall principal component scores (PC1 – C; PC2 – D; PC3 – E) for each sampling site (red – negative; white – positive; expanding symbol legend in yellow in the middle panel).

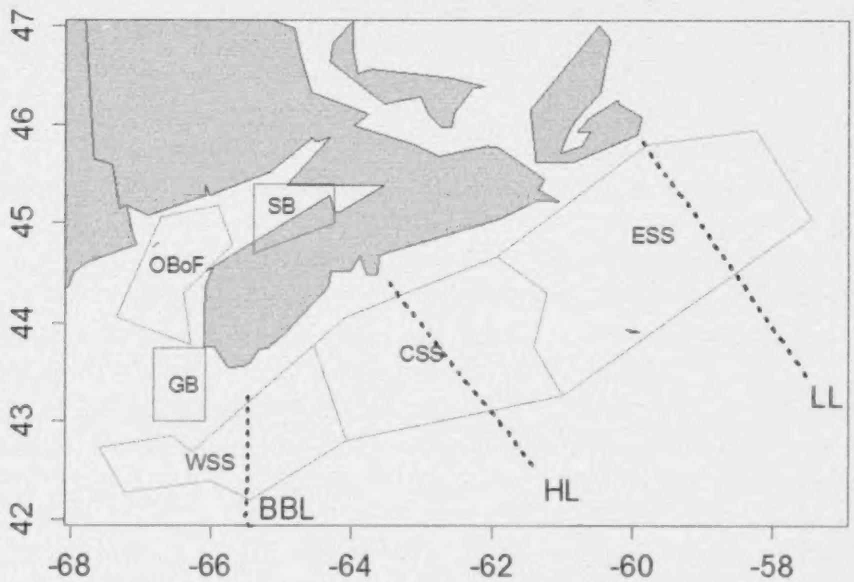


Figure 7. Map of RV survey subregions (red) and commercially fished spawning grounds (blue) for which herring indices were calculated. Index areas include Scotian Shelf (SS), Eastern Scotian Shelf (ESS), Central Scotian Shelf (CSS), Western Scotian Shelf (WSS), outer Bay of Fundy (oBoF), German Bank (GB), and Scots Bay (SB). Scotian Shelf AZMP sections are superimposed as dashed lines (BBL = Brown's Bank Line, HL = Halifax Line, LL = Louisbourg Line).

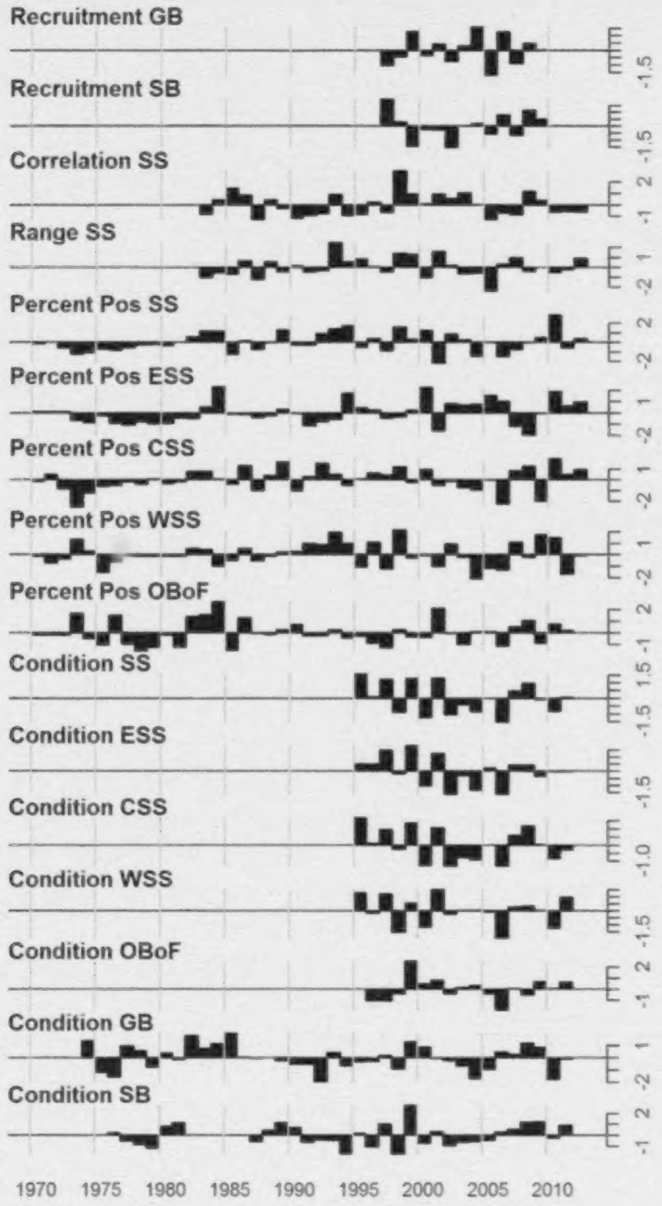


Figure 8. Time series of standardized anomalies for herring indices. Abbreviations for index locations as given in Figure 7. Recruitment estimate was based on differenced biomass at a 3-year lag, correlation is spatial autocorrelation strength at first lag, range is the spatial decorrelation scale, Percent Pos is percent tows positive for herring.

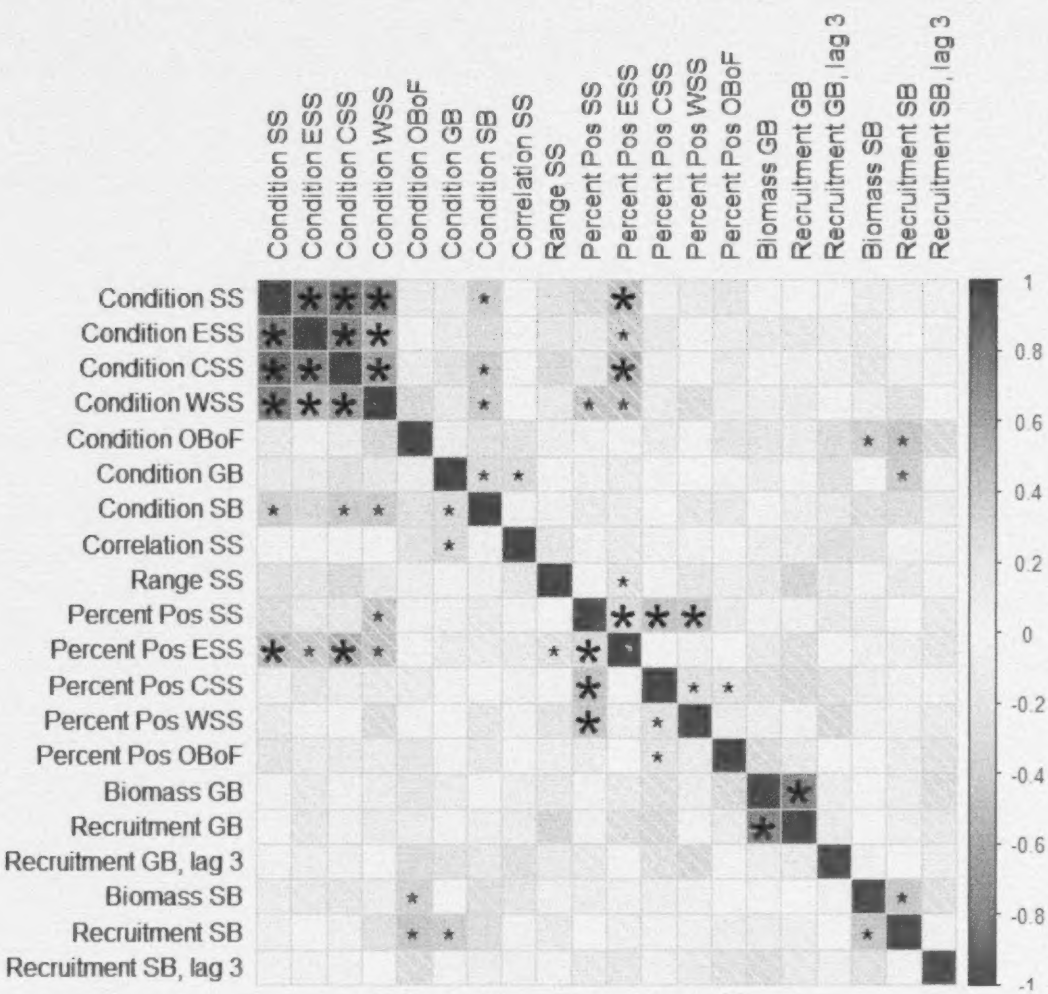


Figure 9. Corrgram of all herring indices. Asterisks indicate low probability, with small asterisks indicating p<0.1, large asterisks p<0.01.

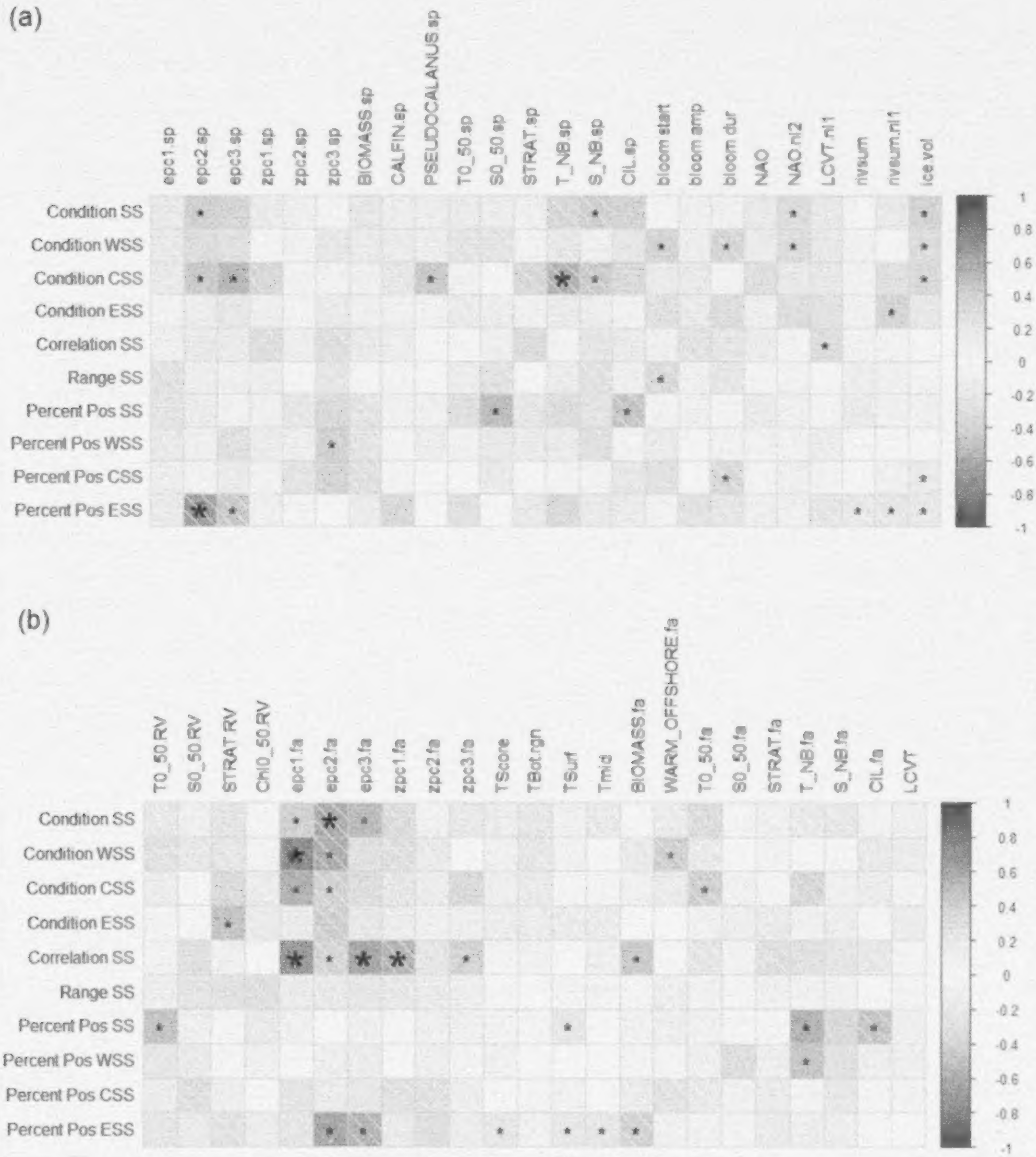


Figure 10. Corrgrams for Scotian Shelf herring indices and (a) predictive pelagic environmental indices and (b) concurrent and retrospective pelagic environmental indices. Environment PC scores are abbreviated as "epc", zooplankton PC scores as "zpc", Labrador Current volume transport as LCVT, negative lags as "nlx" (x=lag), and RV survey metrics as "RV". Spring and fall are "sp" and "fa." Refer to Table 1 and text for further details on variables and number of years represented by each pair.

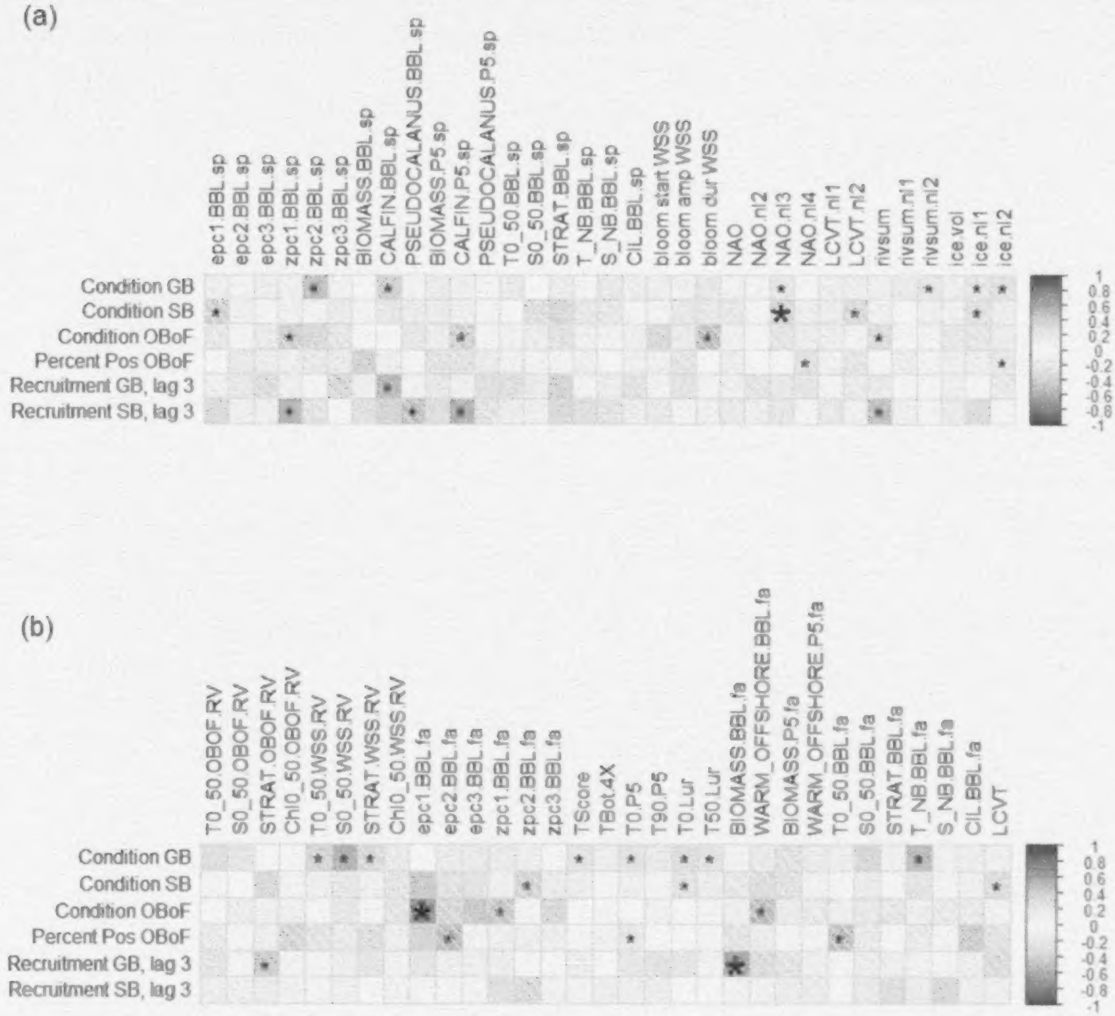
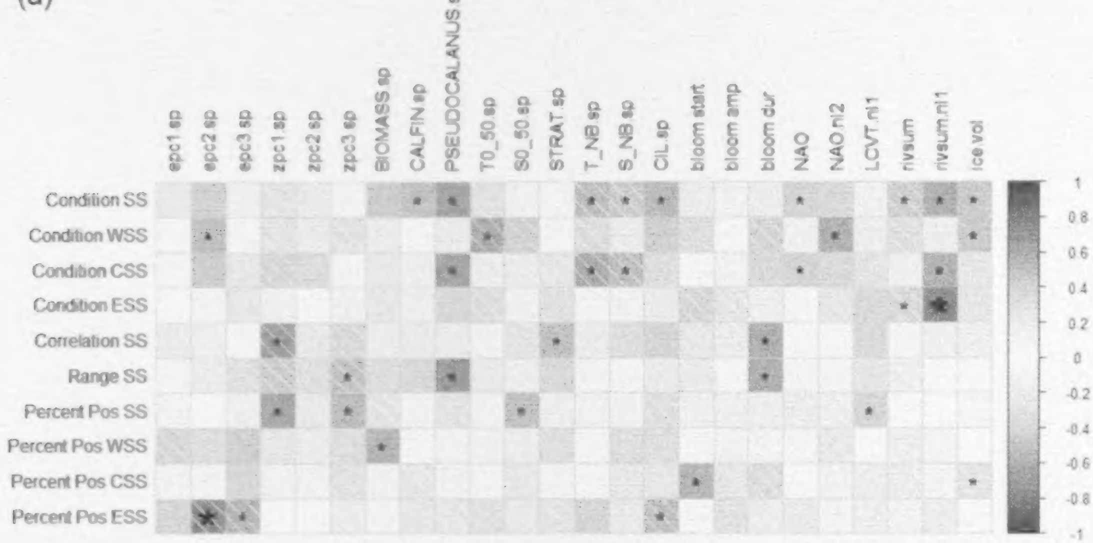


Figure 11. Corrgrams for Southwest Nova herring indices and (a) predictive pelagic environmental indices and (b) concurrent and retrospective pelagic environmental indices. Environment PC scores are abbreviated as "epc", zooplankton PC scores as "zpc", Labrador Current volume transport as LCVT, negative lags as "nlx" (x=lag), and RV survey metrics as "RV". Spring and fall are "sp" and "fa." Refer to Table 1 and text for further details on variables and number of years represented by each pair.

(a)



(b)

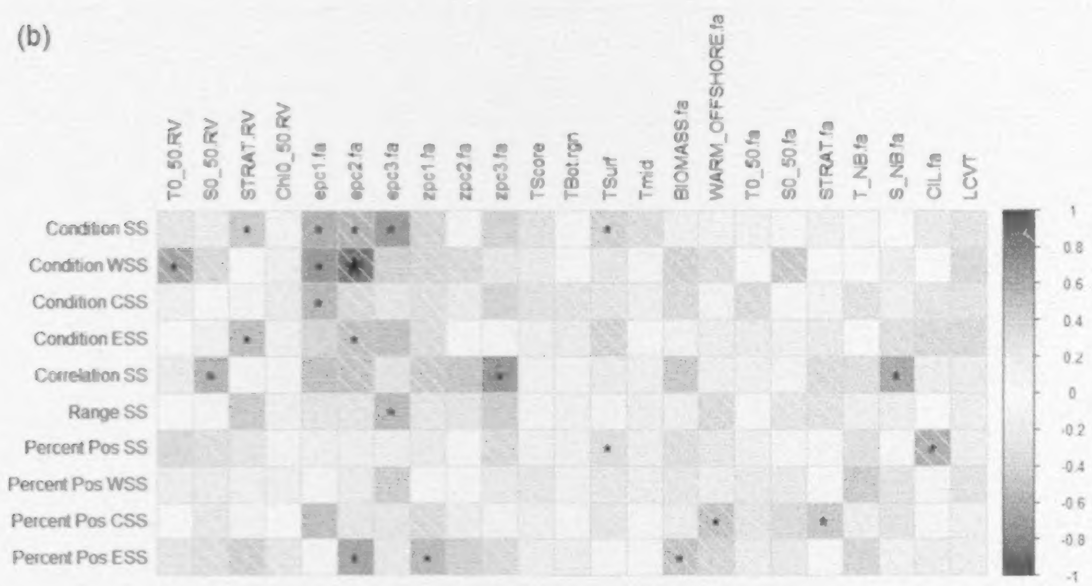
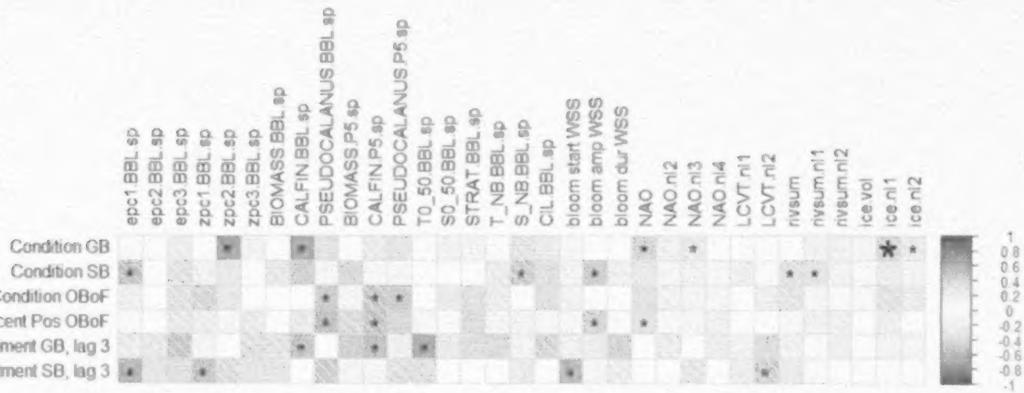


Figure 12. Corrgrams for ordered factors representing bottom, mid-two, and top quartiles of Scotian Shelf herring indices and (a) predictive pelagic environmental indices and (b) concurrent and retrospective pelagic environmental indices. Environment PC scores are abbreviated as "epc", zooplankton PC scores as "zpc", Labrador Current volume transport as LCVT, negative lags as "nlx" (x=lag), and RV survey metrics as "RV". Spring and fall are "sp" and "fa." Refer to Table 1 and text for further details on variables and number of years represented by each pair.

(a)



(b)

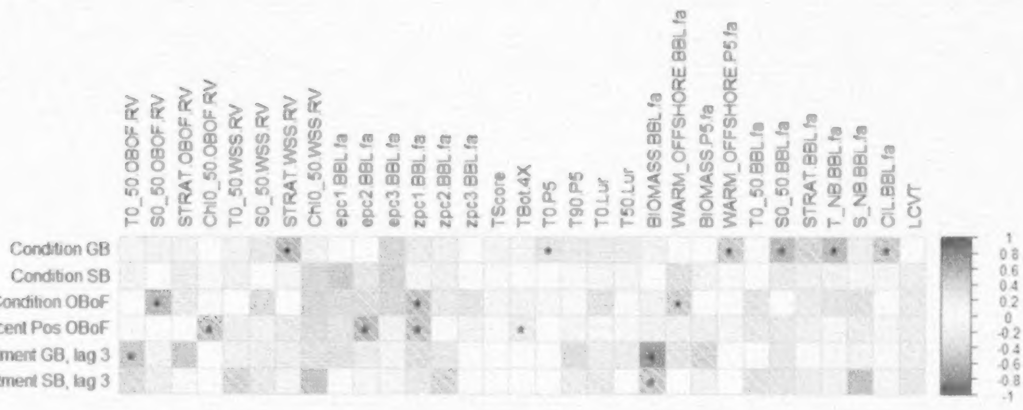


Figure 13. Corrgrams for ordered factors representing bottom, mid-two, and top quartiles of Southwest Nova herring indices and (a) predictive pelagic environmental indices and (b) concurrent and retrospective pelagic environmental indices. Environment PC scores are abbreviated as "epc", zooplankton PC scores as "zpc", Labrador Current volume transport as LCVT, negative lags as "nlx" (x=lag), and RV survey metrics as "RV". Spring and fall are "sp" and "fa." Refer to Table 1 and text for further details on variables and number of years represented by each pair.

APPENDICES

APPENDIX A: AZMP SECTION STATIONS AND NOMINAL DEPTHS

Table A.1. Nominal coordinates and depths for AZMP section stations.

Station Name	Long Name	Latitude	Longitude	Depth [m]
BBL1	BROWNS BANK 1	43.25	-65.48	53
BBL2	BROWNS BANK 2	43	-65.48	122
BBL3	BROWNS BANK 3	42.76	-65.483	107
BBL4	BROWNS BANK 4	42.45	-65.483	101
BBL5	BROWNS BANK 5	42.133	-65.5	179
BBL6	BROWNS BANK 6	42	-65.51	983
BBL7	BROWNS BANK 7	41.867	-65.35	1904
HL1	HALIFAX 1	44.4	-63.45	84
HL2[1]	HALIFAX 2	44.267	-63.317	149
HL3	HALIFAX 3	43.883	-62.883	264
HL4	HALIFAX 4	43.479	-62.451	84
HL5	HALIFAX 5	43.183	-62.098	107
HL6	HALIFAX 6	42.85	-61.733	1035
HL7	HALIFAX 7	42.533	-61.4	2777
LL1	LOUISBOURG 1	45.825	-59.85	85
LL2	LOUISBOURG 2	45.658	-59.702	140
LL3	LOUISBOURG 3	45.492	-59.517	144
LL4	LOUISBOURG 4	45.158	-59.175	102
LL5	LOUISBOURG 5	44.817	-58.85	202
LL6	LOUISBOURG 6	44.475	-58.508	66
LL7	LOUISBOURG 7	44.133	-58.175	728
LL8	LOUISBOURG 8	43.783	-57.833	2868
LL9	LOUISBOURG 9	43.473	-57.527	3672
CSL1/TDC1[2]	CABOT STRAIT 1	46.958	-60.217	78/80
CSL2/TDC2	CABOT STRAIT 2	47.023	-60.117	190 / 186
CSL3/TDC3	CABOT STRAIT 3	47.1	-59.992	321 / 340
CSL4/TDC4	CABOT STRAIT 4	47.272	-59.783	450 / 468
CSL5/TDC5	CABOT STRAIT 5	47.433	-59.558	468 / 477
CSL6/TDC6	CABOT STRAIT 6	47.583	-59.342	257 / 260
TESL1	ST LAWRENCE ESTUARY 1	48.575	-68.488	33
TESL2	ST LAWRENCE ESTUARY 2	48.625	-68.547	217
TESL3[1]	ST LAWRENCE ESTUARY 3	48.667	-68.583	335
TESL4	ST LAWRENCE ESTUARY 4	48.708	-68.63	344
TESL5	ST LAWRENCE ESTUARY 5	48.75	-68.667	346
TESL6	ST LAWRENCE ESTUARY 6	48.788	-68.708	150
TESL7	ST LAWRENCE ESTUARY 7	48.825	-68.75	126
TSI1[1]	SEPT ILES 1	49.242	-66.2	185
TSI2	SEPT ILES 2	49.4	-66.217	342
TSI3	SEPT ILES 3	49.55	-66.233	333
TSI4[1]	SEPT ILES 4	49.717	-66.25	341
TSI5	SEPT ILES 5	49.882	-66.267	278
TSI6	SEPT ILES 6	50.05	-66.283	118
TASO1	SOUTHWEST ANTICOSTI 1	49.217	-64.8	239
TASO2	SOUTHWEST ANTICOSTI 2	49.317	-64.717	379
TASO3	SOUTHWEST ANTICOSTI 3	49.433	-64.617	369
TASO4	SOUTHWEST ANTICOSTI 4	49.55	-64.517	300
TASO5	SOUTHWEST ANTICOSTI 5	49.667	-64.417	168
TIDM1	ILES DE LA MADELEINE 1	46.745	-61	64
TIDM2	ILES DE LA MADELEINE 2	46.83	-61.25	64
TIDM3	ILES DE LA MADELEINE 3	46.902	-61.5	55
TIDM4	ILES DE LA MADELEINE 4	47	-61.75	42
TIDM5	ILES DE LA MADELEINE 5	47.17	-62.25	42
TIDM6	ILES DE LA MADELEINE 6	47.33	-62.75	54
TIDM7	ILES DE LA MADELEINE 7	47.5	-63.25	80
TIDM8	ILES DE LA MADELEINE 8	47.66	-63.75	67
TIDM9	ILES DE LA MADELEINE 9	47.74	-64	84

Station Name	Long Name	Latitude	Longitude	Depth [m]
TIDM10	ILES DE LA MADELEINE 10	47.83	-64.25	43
TCEN1	CENTRAL GULF OF ST LAWRENCE 1	48.21	-61.61	242
TCEN2	CENTRAL GULF OF ST LAWRENCE 2	48.355	-61.45	375
TCEN3	CENTRAL GULF OF ST LAWRENCE 3	48.5	-61.3	412
TCEN4	CENTRAL GULF OF ST LAWRENCE 4	48.647	-61.133	400
TCEN5	CENTRAL GULF OF ST LAWRENCE 5	48.792	-60.973	289
TBB1	BONNE BAY 1	49.343	-58.5	61
TBB2	BONNE BAY 2	49.483	-58.717	129
TBB3	BONNE BAY 3	49.6	-58.967	194
TBB4	BONNE BAY 4	49.725	-59.217	226
TBB5	BONNE BAY 5	49.85	-59.45	264
TBB6	BONNE BAY 6	49.983	-59.683	140
TBB7	BONNE BAY 7	50.1	-59.917	105
SI01	SEAL ISLAND 1	53.233	-55.65	68
SI02	SEAL ISLAND 2	53.333	-55.5	138
SI03	SEAL ISLAND 3	53.41	-55.357	163
SI04	SEAL ISLAND 4	53.533	-55.145	205
SI05	SEAL ISLAND 5	53.617	-55	295
SI06	SEAL ISLAND 6	53.757	-54.777	169
SI07	SEAL ISLAND 7	53.917	-54.5	176
SI08	SEAL ISLAND 8	54.082	-54.217	194
SI09	SEAL ISLAND 9	54.2	-54	216
SI10	SEAL ISLAND 10	54.355	-53.733	237
SI11	SEAL ISLAND 11	54.5	-53.5	326
SI12	SEAL ISLAND 12	54.633	-53.25	704
SI13	SEAL ISLAND 13	54.783	-53	1059
SI14	SEAL ISLAND 14	55.067	-52.5	2653
BB01	BONAVISTA 1	48.8	-52.967	98
BB02	BONAVISTA 2	48.8	-52.75	178
BB03	BONAVISTA 3	48.833	-52.65	256
BB04	BONAVISTA 4	48.917	-52.4	352
BB05	BONAVISTA 5	49.025	-52.067	290
BB06	BONAVISTA 6	49.1	-51.83	298
BB07	BONAVISTA 7	49.19	-51.542	312
BB08	BONAVISTA 8	49.28	-51.28	323
BB09	BONAVISTA 9	49.367	-51.017	340
BB10	BONAVISTA 10	49.517	-50.533	332
BB11	BONAVISTA 11	49.683	-50.017	607
BB12	BONAVISTA 12	49.85	-49.5	1372
BB13	BONAVISTA 13	50	-49	1866
BB14	BONAVISTA 14	50.177	-48.472	2450
BB15	BONAVISTA 15	50.332	-47.947	2624
FC01	FLEMISH CAP 1	47	-52.832	107
FC02	FLEMISH CAP 2	47	-52.705	188
FC03	FLEMISH CAP 3	47	-52.58	159
FC04	FLEMISH CAP 4	47	-52.322	126
FC05	FLEMISH CAP 5	47	-52.033	140
FC06	FLEMISH CAP 6	47	-51.485	101
FC07	FLEMISH CAP 7	47	-51	106
FC08	FLEMISH CAP 8	47	-50.667	177
FC09	FLEMISH CAP 9	47	-50	85
FC10	FLEMISH CAP 10	47	-49.117	82
FC11	FLEMISH CAP 11	47	-48.617	104
FC12	FLEMISH CAP 12	47	-48.117	136
FC13	FLEMISH CAP 13	47	-47.817	168
FC14	FLEMISH CAP 14	47	-47.5	218
FC15	FLEMISH CAP 15	47	-47.25	535
FC16	FLEMISH CAP 16	47	-47.168	860
FC17	FLEMISH CAP 17	47	-47.017	1130
FC18	FLEMISH CAP 18	47	-46.833	1172
FC19	FLEMISH CAP 19	47	-46.67	902
FC20	FLEMISH CAP 20	47	-46.483	350
FC21	FLEMISH CAP 21	47	-46.017	304

Station Name	Long Name	Latitude	Longitude	Depth [m]
FC22	FLEMISH CAP 22	47	-45.73	277
FC23	FLEMISH CAP 23	47	-45.5	250
FC24	FLEMISH CAP 24	47	-45.213	170
FC25	FLEMISH CAP 25	47	-44.988	149
FC26	FLEMISH CAP 26	47	-44.772	150
FC27	FLEMISH CAP 27	47	-44.578	131
FC28	FLEMISH CAP 28	47	-44.433	154
FC29	FLEMISH CAP 29	47	-44.232	276
FC30	FLEMISH CAP 30	47	-44.083	331
FC31	FLEMISH CAP 31	47	-43.833	557
FC32	FLEMISH CAP 32	47	-43.75	675
FC33	FLEMISH CAP 33	47	-43.4	1280
FC34	FLEMISH CAP 34	47	-43.25	3000
FC35	FLEMISH CAP 35	47	-43	3600
FC36	FLEMISH CAP 36	47	-42.75	3700
FC37	FLEMISH CAP 37	47	-42.5	3762
FC38	FLEMISH CAP 38	47	-42	4225
SEGB01	SOUTHEAST GRAND BANK 1	46.583	-52.933	53
SEGB02	SOUTHEAST GRAND BANK 2	46.5	-52.85	181
SEGB03	SOUTHEAST GRAND BANK 3	46.35	-52.733	173
SEGB04	SOUTHEAST GRAND BANK 4	46.208	-52.608	129
SEGB05	SOUTHEAST GRAND BANK 5	46.07	-52.5	92
SEGB06	SOUTHEAST GRAND BANK 6	45.788	-52.267	85
SEGB07	SOUTHEAST GRAND BANK 7	45.458	-52	82
SEGB08	SOUTHEAST GRAND BANK 8	45.095	-51.7	73
SEGB09	SOUTHEAST GRAND BANK 9	44.725	-51.395	71
SEGB10	SOUTHEAST GRAND BANK 10	44.363	-51.103	73
SEGB11	SOUTHEAST GRAND BANK 11	44	-50.808	73
SEGB12	SOUTHEAST GRAND BANK 12	43.633	-50.517	66
SEGB13	SOUTHEAST GRAND BANK 13	43.2	-50.167	67
SEGB14	SOUTHEAST GRAND BANK 14	42.92	-49.942	176
SEGB15	SOUTHEAST GRAND BANK 15	42.85	-49.887	389
SEGB16	SOUTHEAST GRAND BANK 16	42.775	-49.828	1485
SEGB17	SOUTHEAST GRAND BANK 17	42.588	-49.683	2550
SEGB18	SOUTHEAST GRAND BANK 18	42.395	-49.518	2850
SEGB19	SOUTHEAST GRAND BANK 19	42.082	-49.27	3110
SEGB20	SOUTHEAST GRAND BANK 20	41.7	-48.95	3215
SEGB21	SOUTHEAST GRAND BANK 21	41.333	-48.667	3380

[1] The sources of nominal depths at transect stations also sampled at higher frequency as time series stations are reported here as noted in Appendix B. The nominal depths reported here for these stations, which include HL2 (Halifax-2), TESL3 (Rimouski), TSI1 (Gaspé Current), and TSI4 (Anticosti Gyre), may differ slightly from depths that have previously been published on the AZMP website.

[2] Both English and French abbreviations are provided for the Cabot Strait transect, which is sampled by both the Maritimes and Québec regions.

APPENDIX B: DETERMINATION OF NOMINAL DEPTHS FOR MARITIMES STATIONS

Appendix B summarizes the analysis performed to determine nominal depths at the AZMP stations for the Maritimes Sections (Brown's Banks, Halifax Line, Louisbourg Line, and Cabot Strait). The need for a set of nominal depths was identified in order to standardize data processing from various data sources (biological, chemical and physical oceanographic data).

The depths at the station locations were compiled from a variety of sources including:

- Soundings collected at the stations during bottle cast measurements
- Soundings collected during CTD measurements
- Depths at the stations from AZMP cruise reports
- Smith and Sandwell Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings at 1 km resolution V14.1 (NOAA and Scripps Institution of Oceanography) (Smith and Sandwell 1997)
- Canadian Hydrographic Service 64 (CHS64) compilation dataset generated at BIO (T. Spears, personal communication; data compilation created in mid-2000s includes Canadian Hydrographic Service basemap data and other high resolution datasets)
- General Bathymetric Chart of the Oceans (GEBCO) bathymetry data at 1 minute resolution (Gebco Gridded Global Bathymetry Data 2009)
- United States Geological Survey (USGS) bathymetry data at 0.25 minute resolution (source believed to be Roworth and Signell 1998)
- NW Atlantic compilation at 512 m resolution, Canadian Hydrographic Service (CHS) (Varma et al. 2008)

The list of depths from each source is shown in Table B.1, along with the statistics computed using all the sources. All gridded bathymetry data were linearly interpolated to the station locations, and for the Smith and Sandwell grid the nearest neighbour data was considered as well. The box plots with sounding data used to compute depths from CTD and bottle casts are shown on Figure B.1 and B.2, respectively.

Each source was then compared with the mean depth values computed using all the sources (Figure B.3). Note that for some stations there are large differences in depth estimates, while in some cases all the sources agree well. The highest variability was seen for soundings collected during bottle casts (Figure B.2), which also show the greatest discrepancy from the mean values (Figure B.3).

Instead of using mean values for the set of nominal depths it was decided to use a single, citable source that was fairly consistent with the mean depths and CTD measurements. The main contenders in the selection process were the Smith and Sandwell bathymetry, GEBCO and NW Atlantic compilation. The differences from measured CTD depths for those three sources are shown in Figure B.4. The NW Atlantic compilation showed the best agreement with the mean and CTD measurements; it is a fairly recent compilation with the high resolution of 512 m, it is provided by a local reliable source and was therefore chosen as the preferred source.

The NW Atlantic compilation bathymetry data interpolated to the station locations was extracted by DFO's Ocean Data and Information Section on behalf of CHS. The final version of nominal depths at the Maritimes nominal station locations is included in Appendix A. Nominal depths for the Gulf of St. Lawrence transects, which were average depths of soundings taken during station occupations excluding outliers, were provided by Peter Galbraith. The source of nominal depths for stations on the Seal Island, Bonavista, and Flemish Cap transects were ICNAF (1978); nominal depths for the Southeast Grand Bank Line were provided by Eugene Colbourne.

Table B.1. Depth in meters at "core" AZMP station locations in the Maritimes compiled from different data sources with the statistics at the right side of the table.

Station Name	AZMP Cruise Report	Bottles MEAN	CTD MEAN	Sandwell Nearest Neighbour	Sandwell Interpolated	CHS64	GEBCO	USGS	NWA Compilation	All Sources Mean	All Sources S.D.	S.D./Mean [%]
BBL1	65	67	62	67	68.0	55.08	74	60.53	53	64	7	10%
BBL2	116	116.5	113.3	113	114.7	114.79	101	114.44	122	114	6	5%
BBL3	110	104.8	102.2	98	96.4	101.83	100	104.97	107	103	4	4%
BBL4	102	106.3	101.1	101	100.0	96.55	97	100.65	101	101	3	3%
BBL5	90	276.4	189	255	213.8	187.11	207	274.01	179	208	58	28%
BBL6	1100	1095.5	1077.9	1131	1147.8	934.51	775	961.45	983	1023	121	12%
BBL7	1800	1707	1882.2	1911	1928.0	1817.99	1782	1734.63	1904	1830	81	4%
HL1	85	88	88.3	86	89.3	83.09	83	89.03	84	86	3	3%
HL2	168	158.7	156	152	134.0	146.53	112	141.84	149	146	16	11%
HL3	270	259.6	266	172	192.0	261.76	207		264	237	40	17%
HL4	85	85.6	83.8	80	80.3	82.21	98		84	85	6	7%
HL5	100	152.8	100	105	103.1	99.14	99		107	108	18	17%
HL6	1000	962.7	1014.1	1110	1140.7	1022.01	1028		1035	1039	58	6%
HL7	2700	2335.6	2719.7	2843	2841.0	2765.61	2720		2777	2713	162	6%
LL1	90	91.7	92.5	72	80.0	86.19	71		85	84	8	10%
LL2	136	214.8	137.5	138	131.9	126.65	153		140	147	28	19%
LL3	145	214.1	138.3	124	137.3	136.46	136		144	147	28	19%
LL4	100	186.5	103.1	83	84.0	102.67	99		102	108	33	31%
LL5	230	286.5	228.1	256	255.5	231.16	182		202	234	33	14%
LL6	70	124.8	66.1	84	82.2	65.57	68		66	78	20	26%
LL7	750	652.1	721.8	628	649.2	656.22	886		728	709	84	12%
LL8	2800	2392.1	2711.5	2944	2959.6	2903.81	2957		2868	2817	192	7%
LL9	3600	3494.1	3607.6	3746	3743.9	3677.95	3642		3672	3648	83	2%
CSL1	80	86.9	79.4	74	74.0	76.22	77		78	78	4	5%
CSL2	180	189.5	176.1	152	165.5	182.53	174		190	176	13	7%
CSL3	330	348.8	334.9	310	310.3	322.35	304		321	323	15	5%
CSL4	470	468.1	466.4	456	453.3	463.78	439		450	458	11	2%
CSL5	480	478.8	473.7	472	469.6	470.54	457		468	471	7	2%
CSL6	265	267.5	263.4	258	261.1	235.12	298		257	263	17	7%

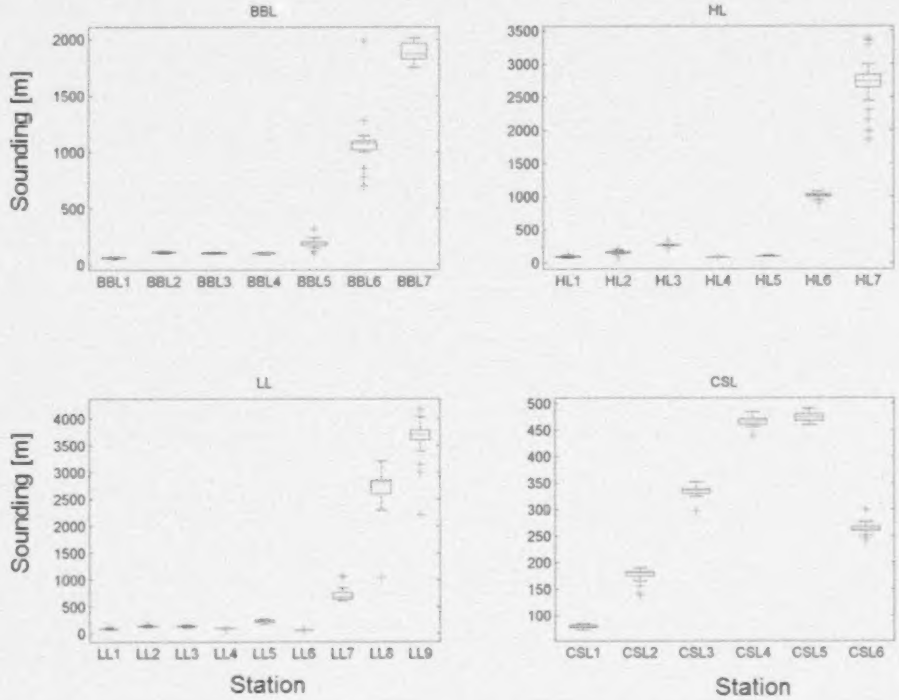


Figure B.1. Box plots of the soundings at AZMP stations from CTD data. Outliers are shown in red.

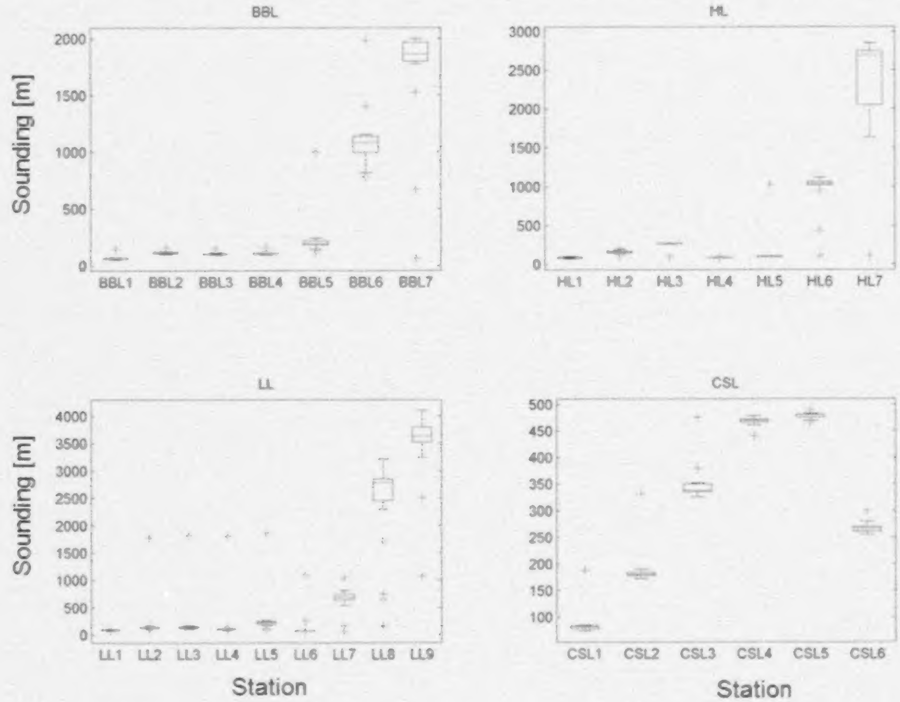


Figure B.2. Box plots of the soundings at AZMP stations from bottle casts. Outliers are shown in red.

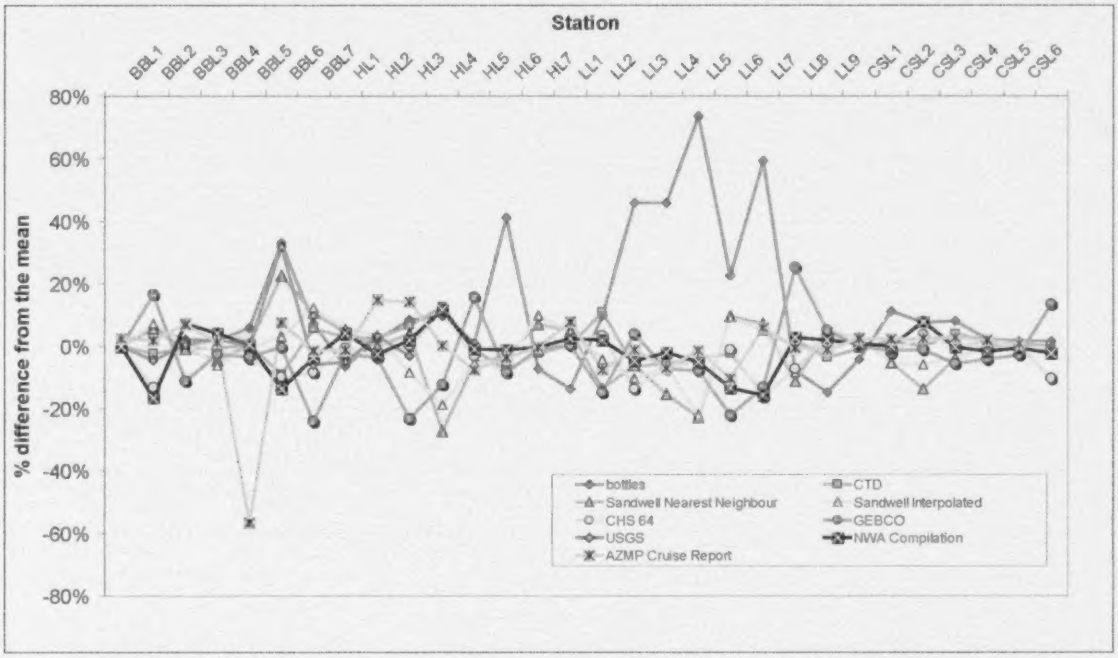


Figure B.3. Percentage difference from the mean depth at the stations estimated from nine data sources. The sources are shown in the legend.

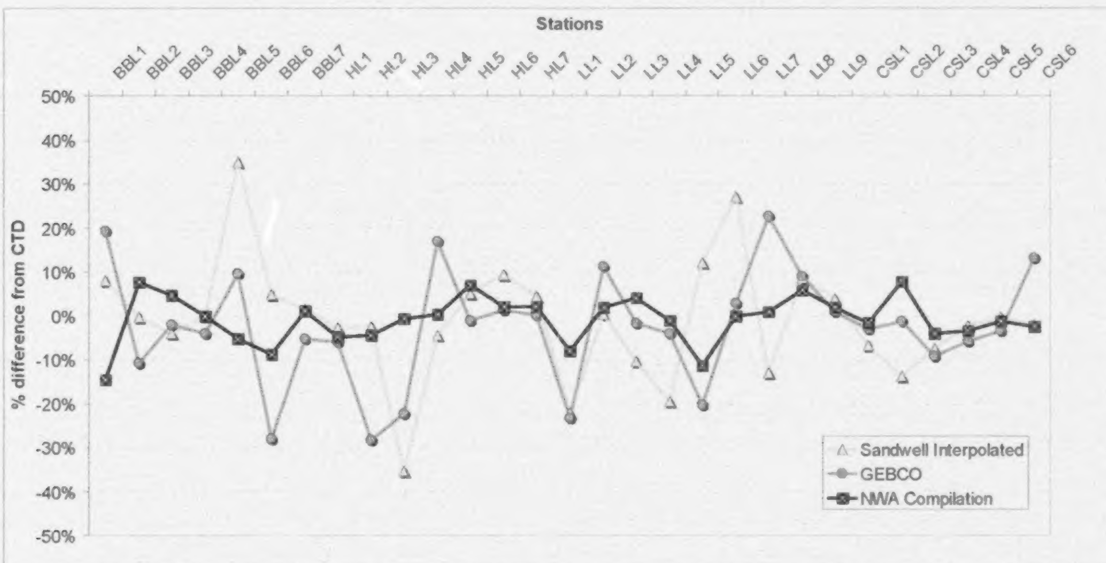


Figure B.4. Percent difference from the CTD soundings measured at the stations for the three sources shown in the legend.

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APPENDIX C: AZMP BOTTLE DATA COMPILATION

Maritimes Nutrient and Chlorophyll-a Data

AZMP data for the Maritimes Region extracted from BioChem contained multiple headers for chlorophyll-a and all the nutrients, indicating that each parameter was derived using different methods (BioChem code table, M. Kennedy, personal communication). This appendix provides an inventory of the AZMP Maritimes data and documents the working dataset used for the SPERA Pelagic Habitat Indicators project. The data inventory is presented in Table C.1, and the temporal distribution of the nutrient methods in Figure C.1 and chlorophyll methods in Figure C.2. For Maritimes data there was no overlap between the data under different headers, so all the data were merged into a final Chlorophyll-a and nutrient dataset.

The majority of Chlorophyll-a data were recorded under CHL_A_HOLM_HANSEN_SF and CHL_A (i.e. unknown method). For the majority of nutrient data, the analysis method was 'not assigned' (NO3_NO2NO3_0, PO4_0, SIO4_0). Note that the extension '0' refers to 'unknown method'; 'F' to the samples frozen to -20°C, and 'SF' to samples frozen to -196°C.

Table C.1. AZMP Maritimes data inventory for chlorophyll-a and nutrients. Total number of samples: 8972.

Header	% data records	Total records
CHL_A	39.2%	6688
CHL_A_HOLM_HANSEN_SF	59%	
CHL_A_HOLM_HANSEN_F	0.4%	
CHL_A_WELSCHMEYER_SF	1.4%	
NO3_NO2NO3_0	94.5%	8762
NO2NO3_ALP_F	4.1%	
NO2NO3_TECH_SF	0.8%	
NO2NO3_ALP_SF	0.6%	
PO4_0	98.5%	8216
PO4_ALP_SF	0.6%	
PO4_TECH_SF	0.9%	
SIO4_0	94.5%	8762
SIO4_ALP_F	4.1%	
SIO4_TECH_SF	1.4%	

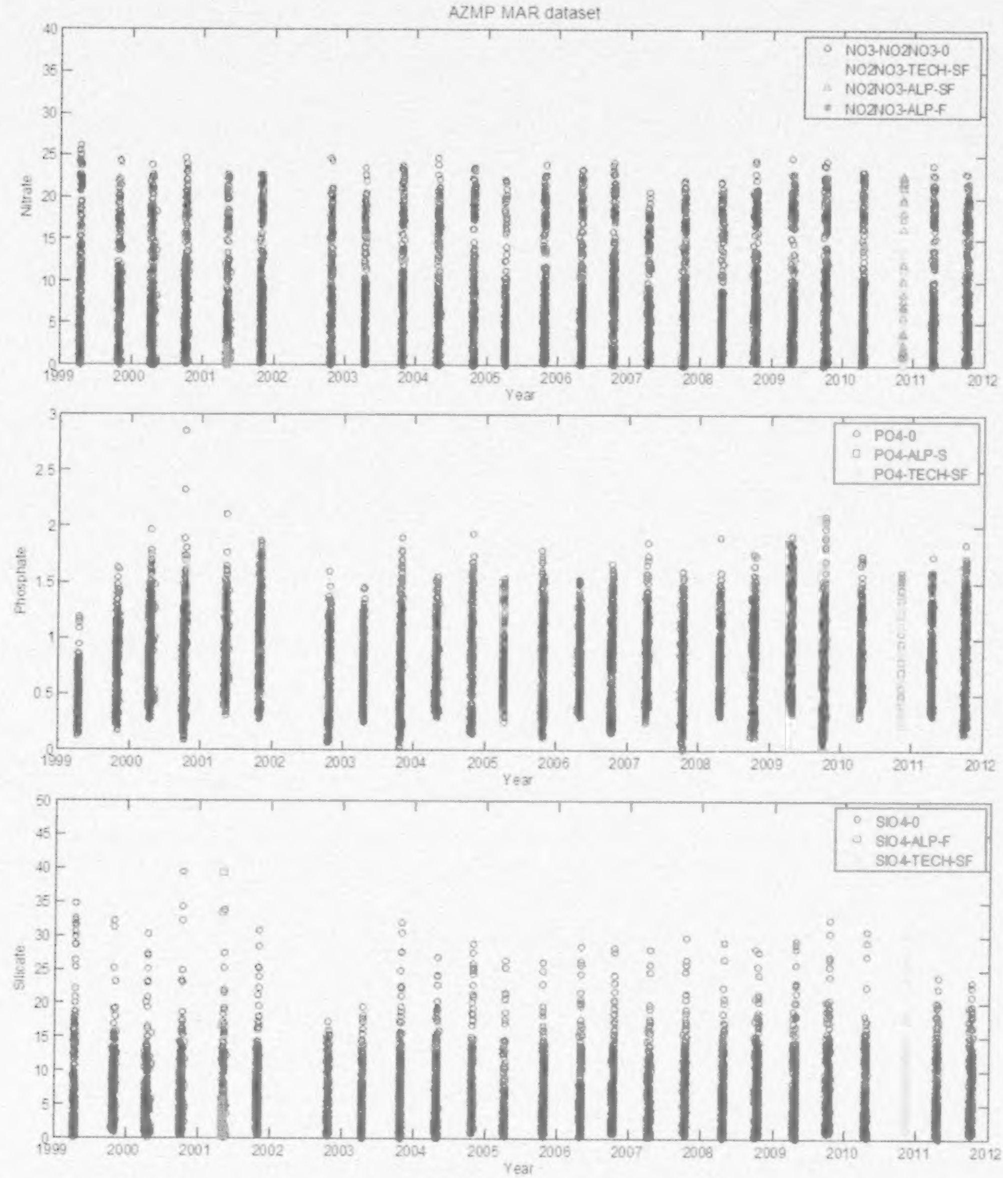

Figure C.1. Distribution among years of AZMP Maritimes nutrient data under different headers that represent different sample analysis methods (shown in the legend).

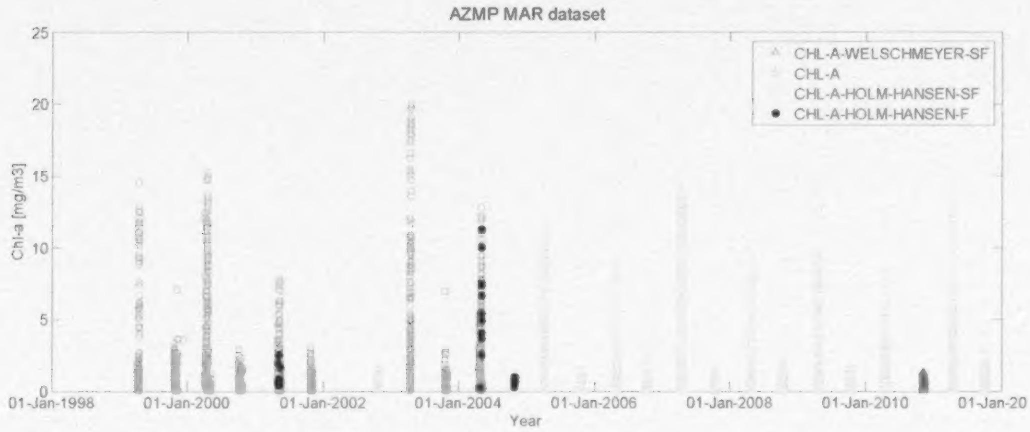

Figure C.2. Dstribution among years of AZMP chlorophyll-a data for the Maritimes Region under different headers that represent different or unspecified sample analysis methods (shown in the legend).

Québec Nutrient and Chlorophyll-a Data

AZMP data for Québec region extracted from BioChem contained two headers for each chlorophyll-a and nutrient, indicating that each parameter was derived using one of two possible methods. This section provides a data inventory (Table C.2) and summarizes the decisions made regarding data selection. Temporal distributions of the chlorophyll and nutrient methods are presented in Figure C.3.

In the case of chlorophyll-a, 18.9% of the data were estimated using the Holm-Hansen method and 98.6% were estimated using the Welschmeyer method. Both methods were used in 17.5% of the data (1115 cases with data for both methods), and only 1.4% of the cases (87 points) were estimated solely with the Holm-Hansen method (Table C.2). The Welschmeyer method underestimated chlorophyll compared to the Holm-Hansen method (Figure C.4). However, for the 1.4% of data for which only the Holm-Hansen method was used, chlorophyll was in the range 0.01-2.37 mg/m^3, and the correction would be smaller than the standard deviation of the data in that region. Therefore, the correction for Holm-Hansen method to match Welschmeyer method was not used.

For each nutrient (nitrate, phosphate and silicate), there were only 10 cases for which data were available for both methods, and in all three cases the methods produced similar results (figure C.5).

The analysis led to the following conclusions:

- For Chlorophyll, use all CHL_A_WELSCHMEYER records and only for missing data use CHL_A_HOLM_HANSEN. Even though the methods produce different results for chlorophyll-a (Figure C.4), the number of values using HOLM_HANSEN only were low, so data correction was not performed as it is most likely not needed for that range of values.
- For nutrients, use the method available, since the overlap is minimal and both methods seem to produce similar results (Figure C.5). For overlapping cases use ALP (10 points only).

Table C.2. Summary of the chlorophyll-a and nutrient data inventory for AZMP Québec region. Total number of samples: 8024.

Parameter	% data records	% overlap	Total No. records	No. overlap records
CHL_A_HOLM_HANSEN_SF	18.9%	17.5%	6360	1115
CHL_A_WELSCHMEYER_SF	98.6%			
NO2NO3_ALP_SF	77.4%	0.12%	8011	10
NO2NO3_TECH_SF	22.7%			
PO4_ALP_SF	77.4%	0.12%	8011	10
PO4_TECH_SF	22.7%			
SIO4_ALP_SF	36.4%	0.12%	8003	10
SIO4_TECH_SF	63.7%			

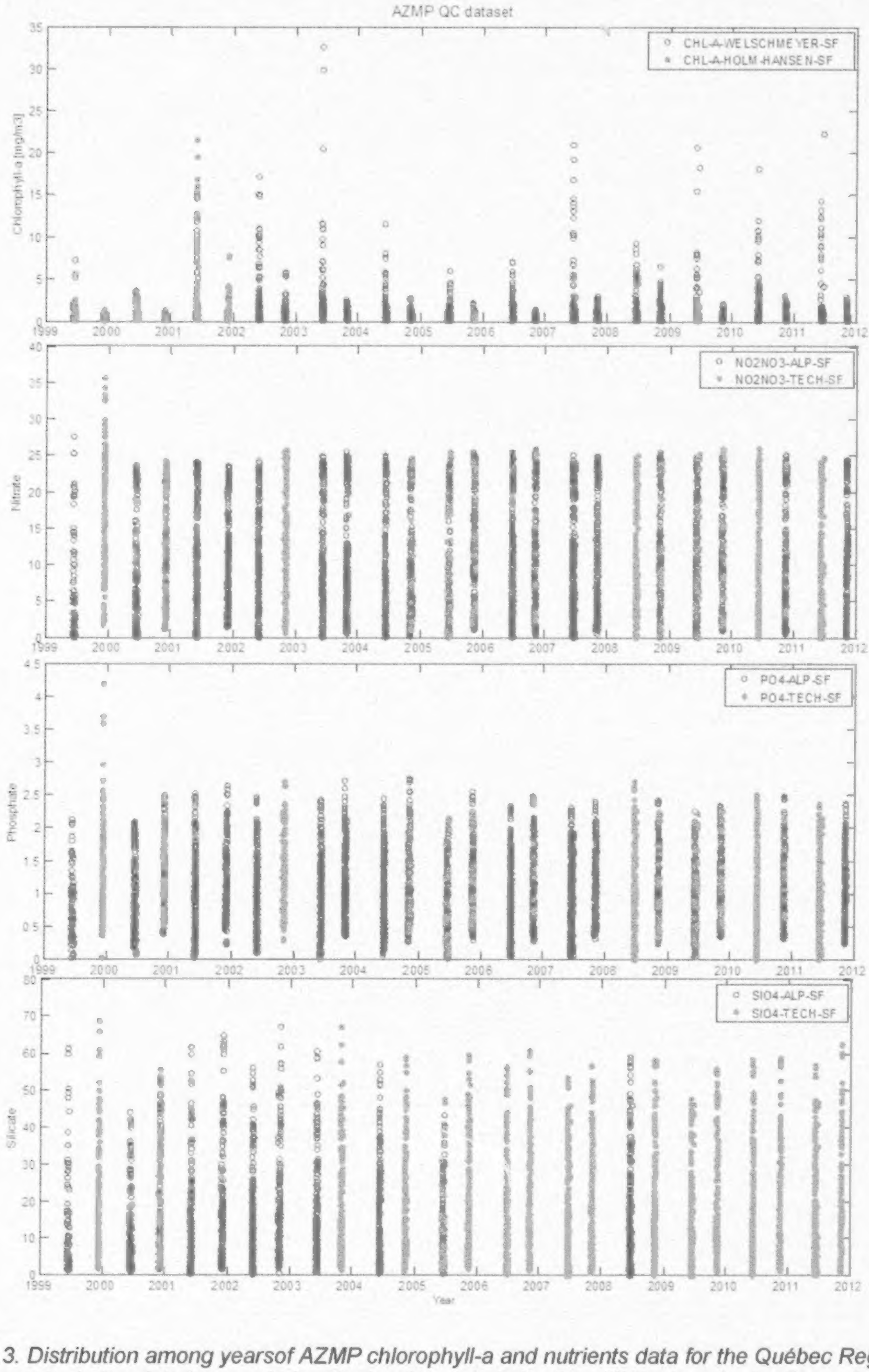

Figure C.3. Distribution among yearsof AZMP chlorophyll-a and nutrients data for the Québec Region. Each parameter in the data is recorded under two headers indicating different methods of sample analysis.

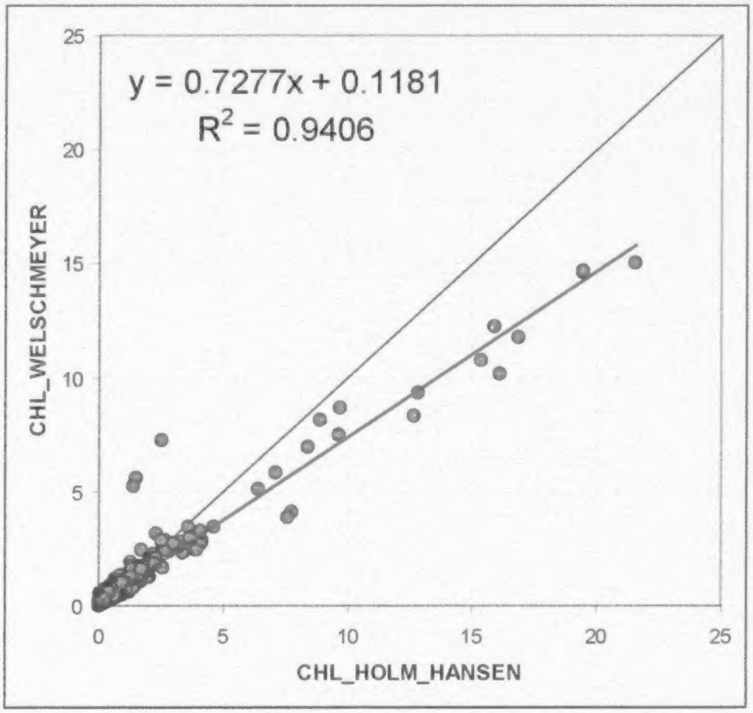

Figure C.4. Comparison between chlorophyll-a concentrations measured using both the Welschmeyer and Holm-Hanson methods in the AZMP Québec data set. There were 1115 records where chlorophyll was derived by both methods. The relationship between the methods could be used for data adjustment.

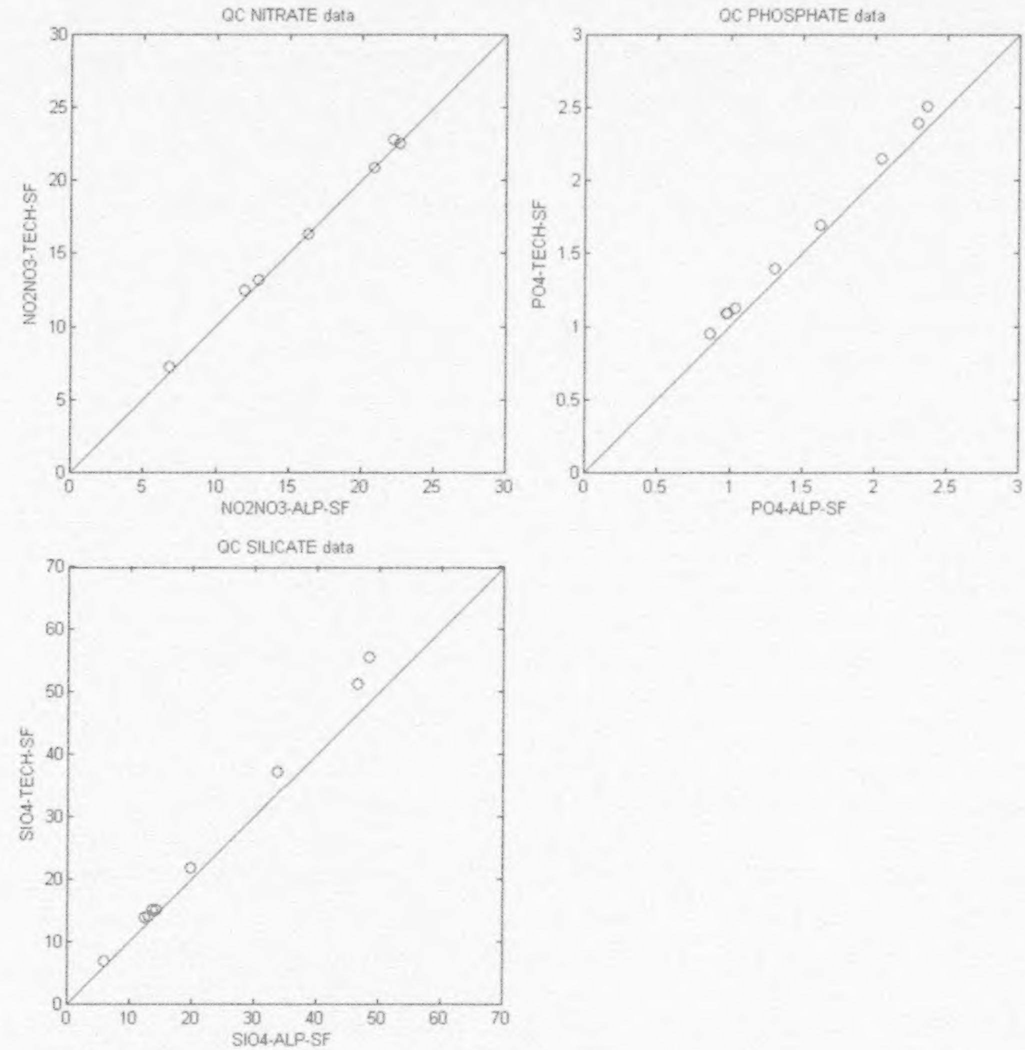

Figure C.5. Nutrient data comparison between the values determined by different methods. For all nutrients (nitrate, silicate and phosphate) there were only 10 records where the parameters were derived by different methods.

Newfoundland Nutrient and Chlorophyll-a Data

The bottle data from Newfoundland were not available in BioChem and were provided by the investigators in the Newfoundland region. Quality control was performed by the Newfoundland group on the bottle dataset by comparing the profiles with the climatology records from the World Ocean Database and applying appropriate flags to the data in order to screen out the suspect profiles.

APPENDIX D: DISCRETE PROFILE INTEGRATION FUNCTION

A script for vertical integration of the discrete nutrient and chlorophyll bottle data was written and used to process all AZMP data from the Maritimes, Québec, and Newfoundland regions used in the Pelagic Habitat Indicators project. This summary provides a brief description of the work accomplished so far.

The development included creation of two components:

1. Standard water column integration function for the discrete profiles
2. Main script that sorts the data and feeds it to the integration function

Integration Function

A Matlab function (integrate_trapz.m) was created to integrate bottle profile data over desired layer in the water column which is defined by the user choosing 'top_limit' and 'bottom_limit' of the layer. The integration itself is performed using standard Matlab trapz.m function. The function is called from Matlab as:

```
p_int=integrate_trapz(depth, parameter, top_limit, bottom_limit)
```

The integration function is fairly simple and self-explanatory. Matlab code is included at the end of this document. An illustration of the integration method and associated assumptions is shown in Figure D.1, and the integration function flowchart in Figure D.2.

Main Script

The "Main Script" that sorts the data and feeds them to the integration function was slightly different for each region due to the different input data content and formats. The main feature of the script is that it imports a lookup table with the nominal depths for all AZMP stations, decides the bottom limit of the integration for each profile (150 m or nominal depth), and extrapolates the value of the parameter to the bottom limit depth (see Figure D.1). The flowchart is a bit complicated, as the bottom limit depth decision has to cover many cases. In the end, integrated nutrient, excess nutrient, and chlorophyll data are exported to the csv (comma separated values) file and Matlab dataset.

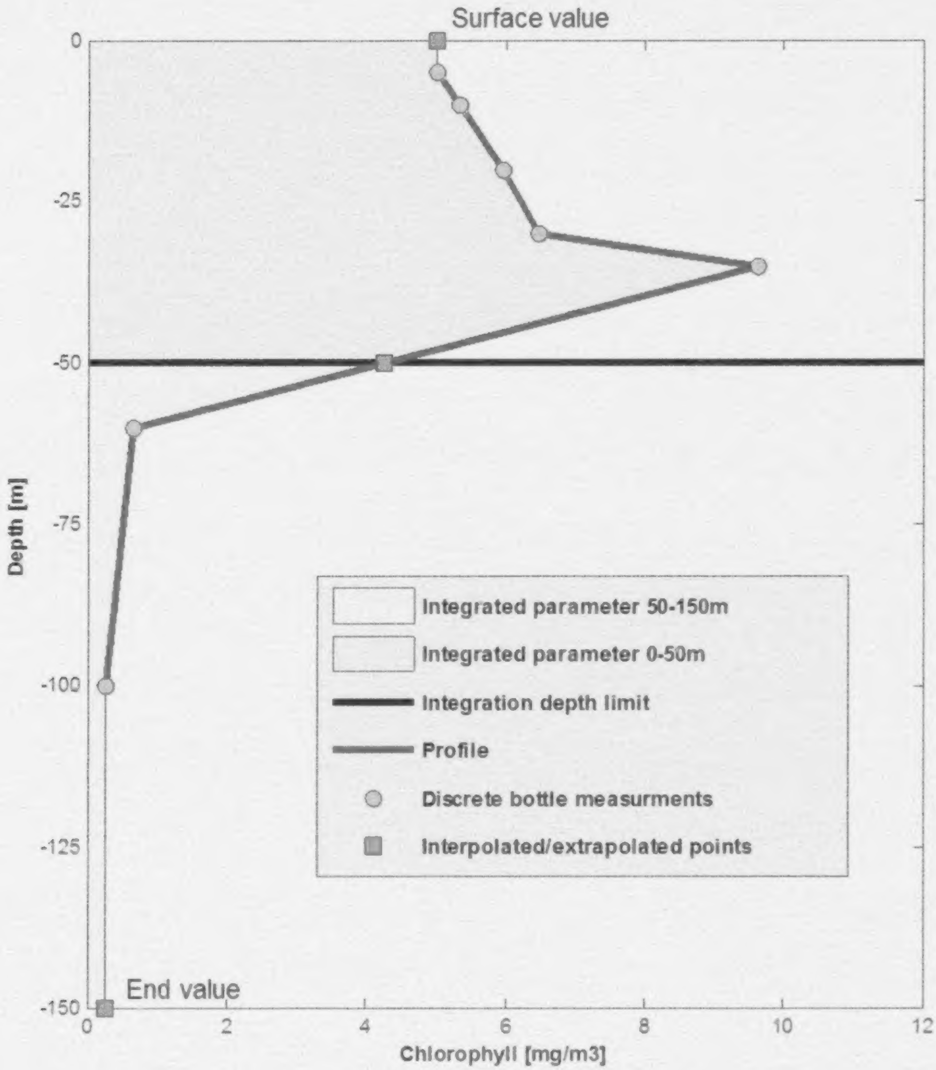

Figure D.1. Illustration of BIO discrete bottle data integration method for the layers 0-50 m and 50-150 m. If the parameter is not measured at the integration limit depths (top_lim or bottom_lim) it is interpolated to those depths if possible. If the depth limits are outside of the measured depth range the values at the depth limits are extrapolated as following: measured profile is extrapolated to the 0 m depth assuming that the surface value of the parameter is equal to the value measured closest to the surface; the end value of the profile is extrapolated assuming that the parameter value at 150 m (or bottom) is equal to the deepest measurement available.

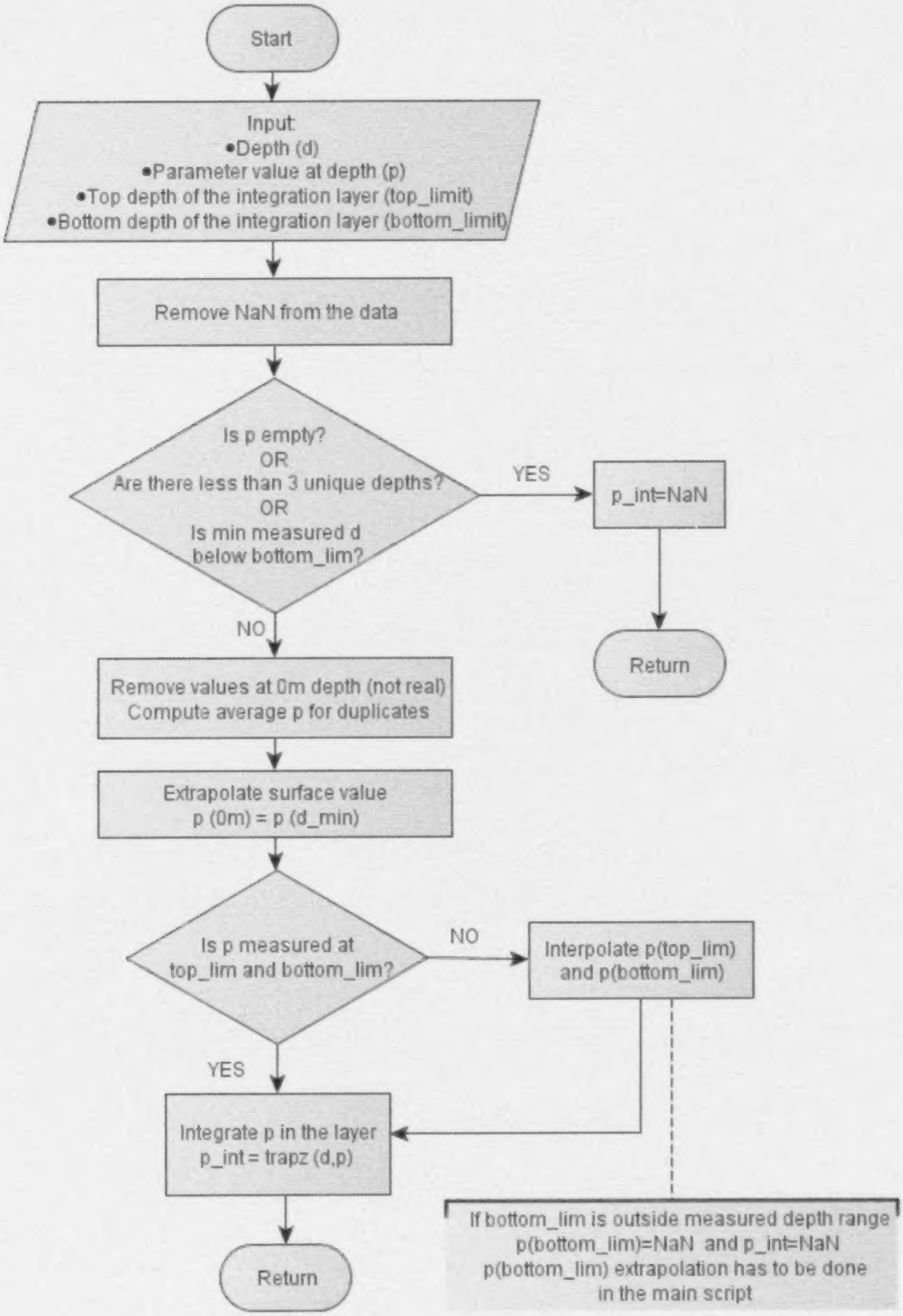

Figure D.2. Flowchart for BIO discrete-profile water-column layer integration function.

Matlab integration function:

```
p_int=integrate_trapz(depth, parameter, top_limit, bottom_limit)

%Function to integrate discrete bottle profiles within a water column layer
%defined by top and bottom depth limits chosen by the user.
%The function is using trpezoid integration in matlab.
%
%Input (one profile at the time):
% d - depth (positive number)
% p - parameter measured at depth d
% top_lim - top depth of the layer
% bottom_lim - bottom depth of the layer
%
%Output:
% p_int - integrated value of the parameter in the desired depth layer
%
%For example to integrate parameter in the layer from 30m to 60m:
%        p_int=integrate_trapz(d,p,30,60)
%
%Notes:
% - Input profiles could contain NaN and those are removed in the function
%    before processing
% - Function extrapolates parameter to 0m depth assuming
%    p(surface)=p(minimum measured depth)
% - Bottom integration depth limits must be within data depths. If outside
%    measured depth limits it returns p_int=NaN
%
%Written by Gordana Lazin, September 25, 2012 for SPERA project
%(PI:Catherine Johnson)

function p_int=integrate_trapz(d,p,top_lim,bottom_lim)

%remove NaN-s from the profile data
d=d(find(~isnan(p))); %depths that contain data
p=p(find(~isnan(p))); %coresponding non-NaN nutrient data

%check if there is profile data, if there are more than 2 unique depths,
%and if the min measured depth is above integration depth
if isempty(p)|(length(unique(d))<=2)|(min(d)>bottom_lim)
    p_int=NaN;
    return
end;

%sort the data by depth
ex=sortrows([d p],1);

%delete data at 0m depths - not real
ex(find(ex(:,1)==0),:)=[];
d=ex(:,1);
p=ex(:,2);

%get rid of duplicates
    ud=unique(d); %check how many unique depths there are
    for ji=1:length(ud)
        indD=find(d==ud(ji));
        jnk(ji,:)=mean(ex(indD,:),1); %compute mean of the duplicates
    end

%re-assign d and p
d=jnk(:,1);
p=jnk(:,2);
```

```
%Add surface value assuming that the first measured value is the same at
%the surface at 0m
d=[0;d]; %add 0m depth
p=[p(1);p]; %add parameter at 0m depth

%Is the parameter measured at the top of the layer or it has to be interpolated?
if find(d==top_lim) %is top depth measured?
     p_top=p(find(d==top_lim)); %if so take parameter at that depth
else
p_top=interp1(d,p,top_lim); %if not measured interpolate top value
end

%Is the parameter measured at the bottom of the layer or it has to be interpolated?
if find(d==bottom_lim) %is bottom depth measured?
     p_bottom=p(find(d==bottom_lim)); %if so take measured value
else
     p_bottom=interp1(d,p,bottom_lim); %if not interpolate
end

%take only the depths of interest (layer)
layer=find(top_lim<d & d<bottom_lim); %indices of the measured depths within the layer

%depths and parameter values within the layer
dl=[top_lim;d(layer);bottom_lim]; %depths within the layer
pl=[p_top;p(layer);p_bottom]; %parameter values within the layer

p_int=trapz(dl,pl); %integrate the parameter within depth layer
```

APPENDIX E: MAPS OF THE ENVIRONMENTAL VARIABLES

Spatial data plots were created for climatologies of 18 variables in spring and fall. For each variable and season, two plots were created:

- **Seasonal Mean** – The average value at each station using all the data in the period 1999-2011. It was plotted if there were more than two data points (station visited at least twice in that time period).
- **Standard Deviation of Seasonal Anomaly** – Seasonal anomalies (i.e. value of the parameter at each station/season/year – mean of the parameter for the station/season across years) were determined using a reference period 1999-2010 and were computed only if there were more than four years of data in the reference period. The low threshold number of years required for the reference period was chosen to include most of the stations.

At the Cabot Strait stations, values from Québec occupations obscure the values from Maritimes occupations plotted below.

Table E.1. List of figures in Appendix E.

Figure Number	Description
E.1	Average temperature, 0-50 m
E.2	Near-bottom temperature
E.3	CIL thickness
E.4	Minimum temperature
E.5	Depth of temperature minimum
E.6	Depth of temperature minimum only at stations where it is < 125 m
E.7	Average salinity, 0-50 m
E.8	Near-bottom salinity
E.9	Stratification index
E.10	Average oxygen concentration, 0-50 m
E.11	Integrated chlorophyll, 0-100 m
E.12	Integrated nitrate, 0-50 m
E.13	Integrated nitrate, 50-150 m, or 50 m to bottom
E.14	Integrated phosphate, 0-50 m
E.15	Integrated phosphate, 50-150 m, or 50 m to bottom
E.16	Integrated silicate, 0-50 m
E.17	Integrated silicate, 50-150 m, or 50 m to bottom
E.18	Excess phosphate, 0-50 m
E.19	Excess silicate, 0-50 m

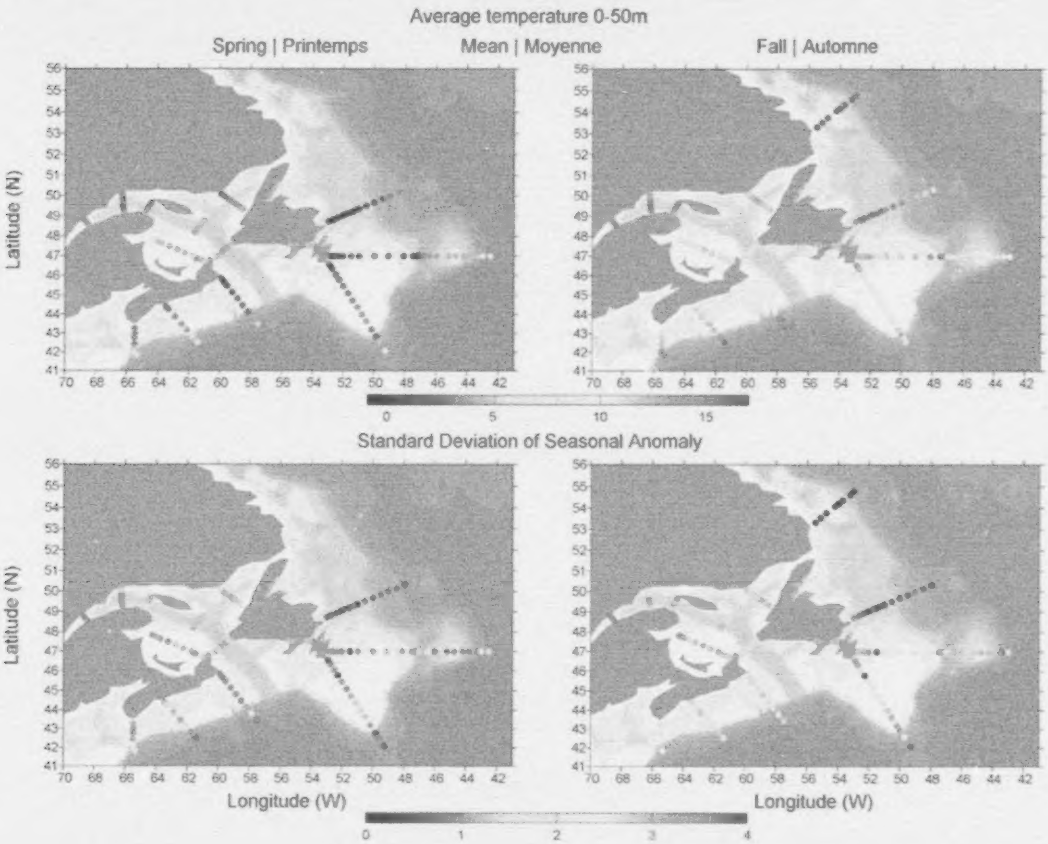

Figure E.1. Average temperature (°C) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

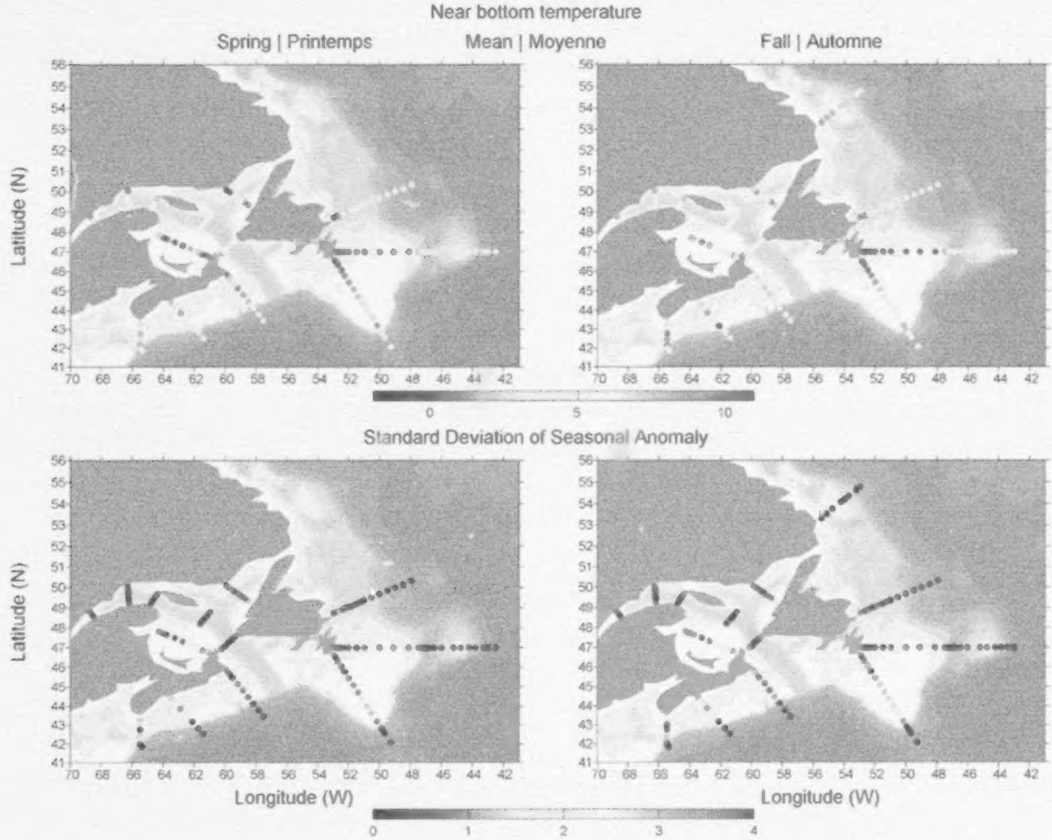

Figure E.2. Average near bottom temperature (°C) and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

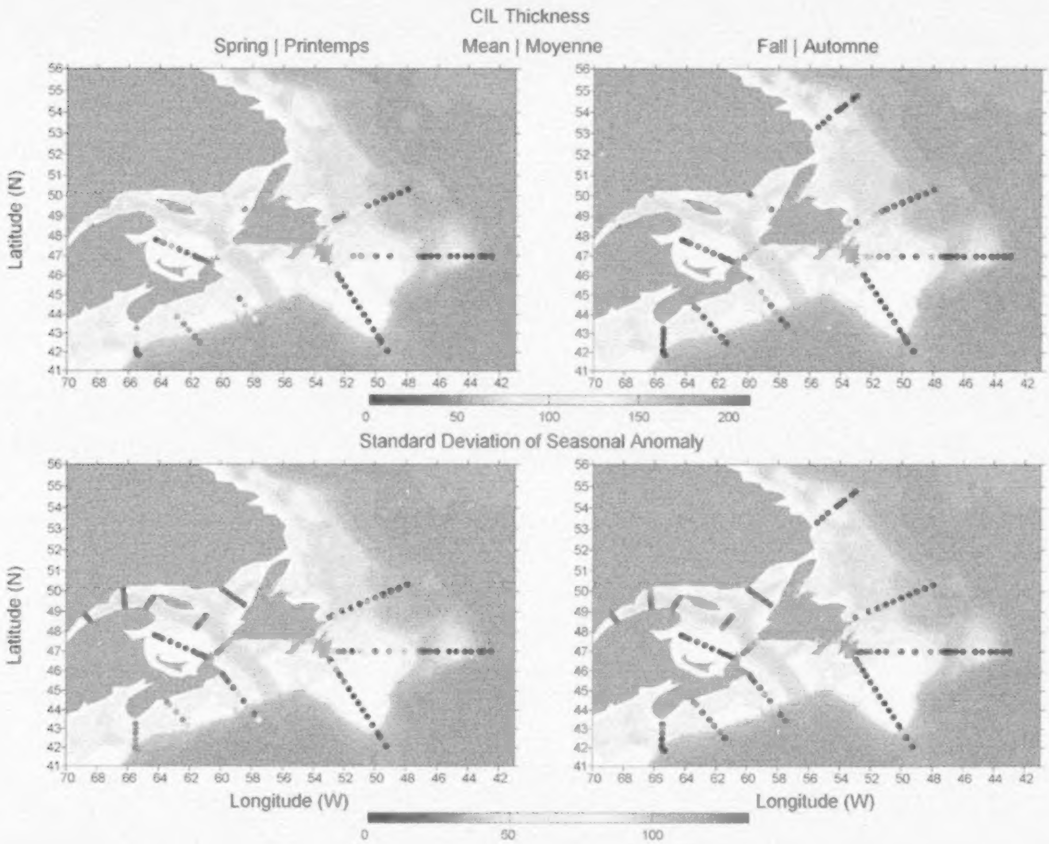

Figure E.3. Average thickness (m) of the CIL and standard deviation of seasonal anomaly at each AZMP station, 1999-2011. The CIL boundaries are defined as 0°C in the Newfoundland region, 2°C in the Gulf of St. Lawrence, and 4°C on the Scotian Shelf.

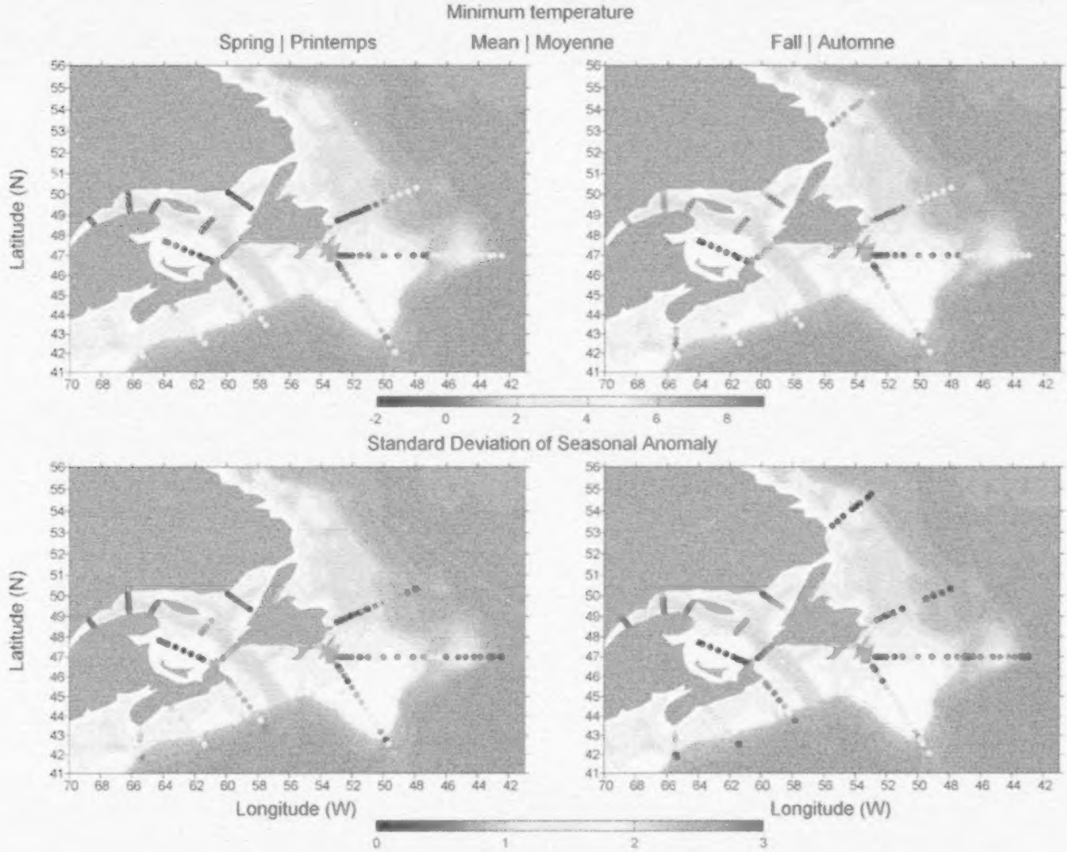

Figure E.4. Average minimum temperature (°C) and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

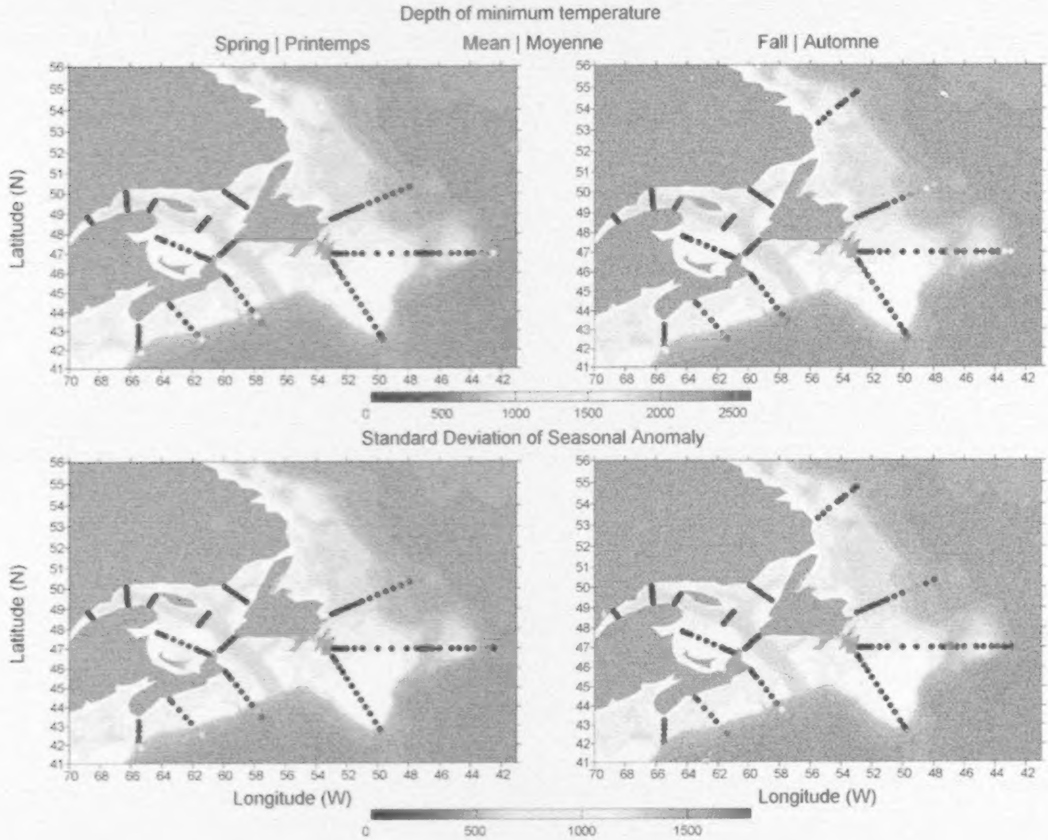

Figure E.5. Average depth of minimum temperature (m) and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

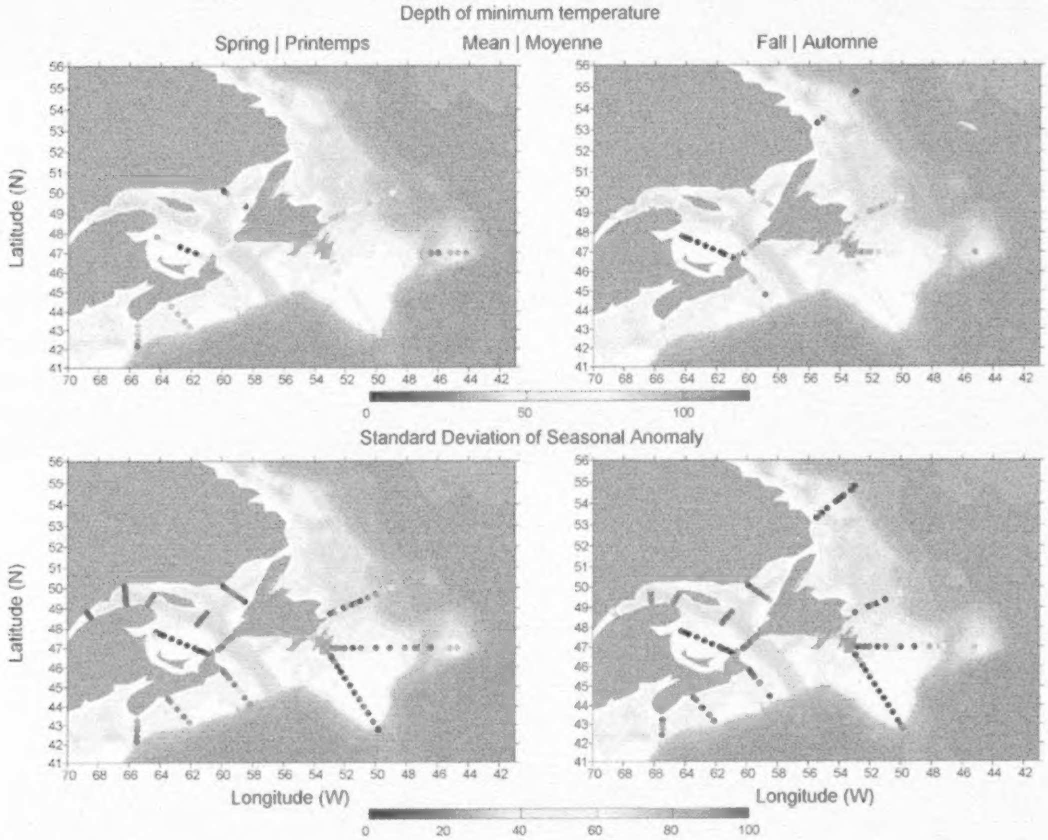

Figure E.6. Average depth of minimum temperature (m) and standard deviation of seasonal anomaly at AZMP stations where the depth of the temperature minimum is less than 125 m, 1999-2011.

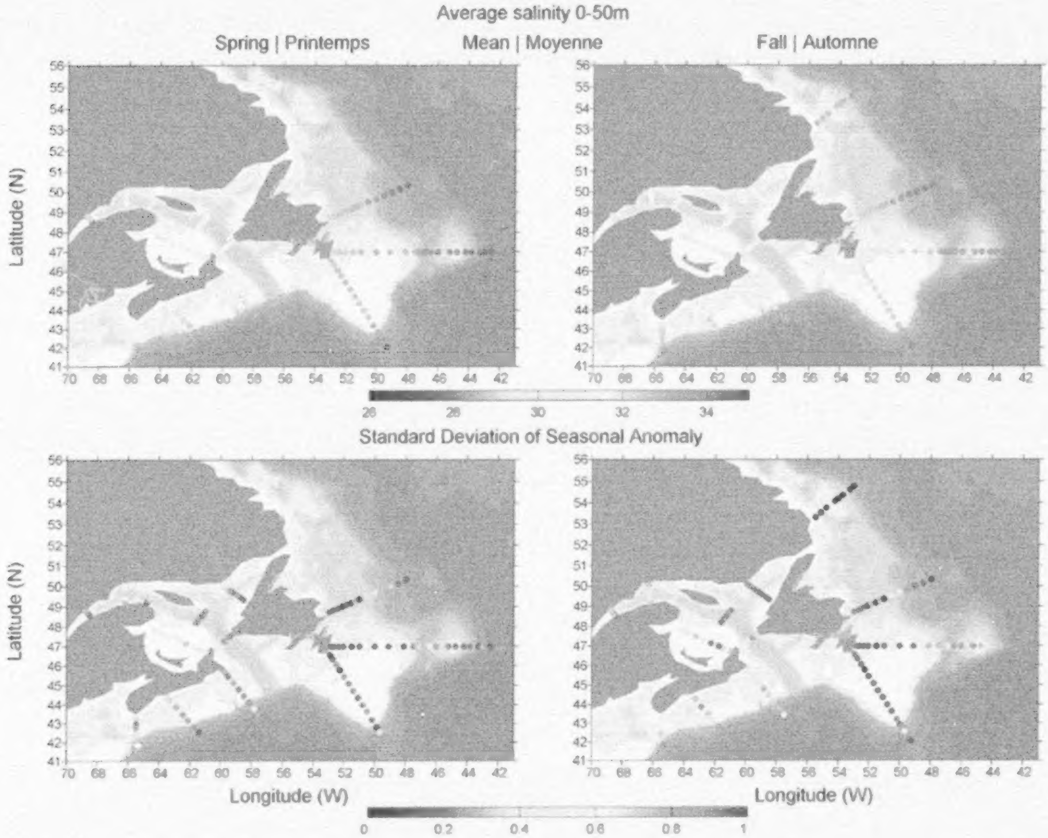

Figure E.7. Average salinity (psu) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

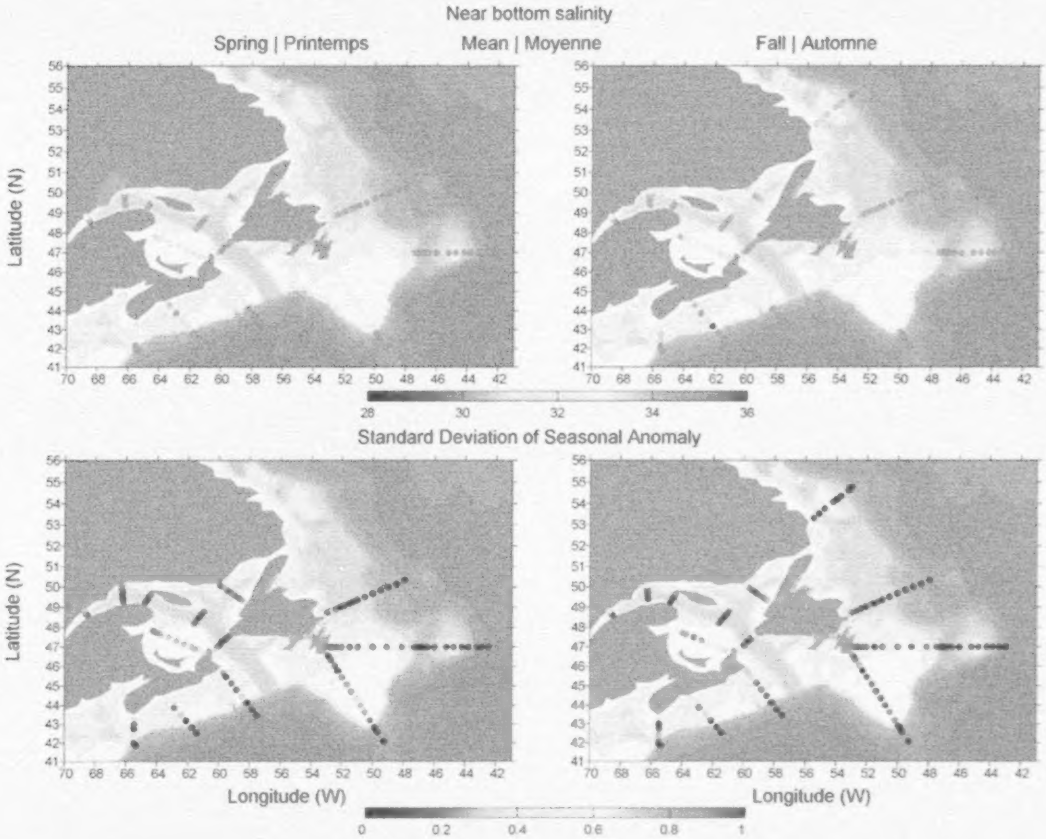

Figure E.8. Average near bottom salinity (psu) and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

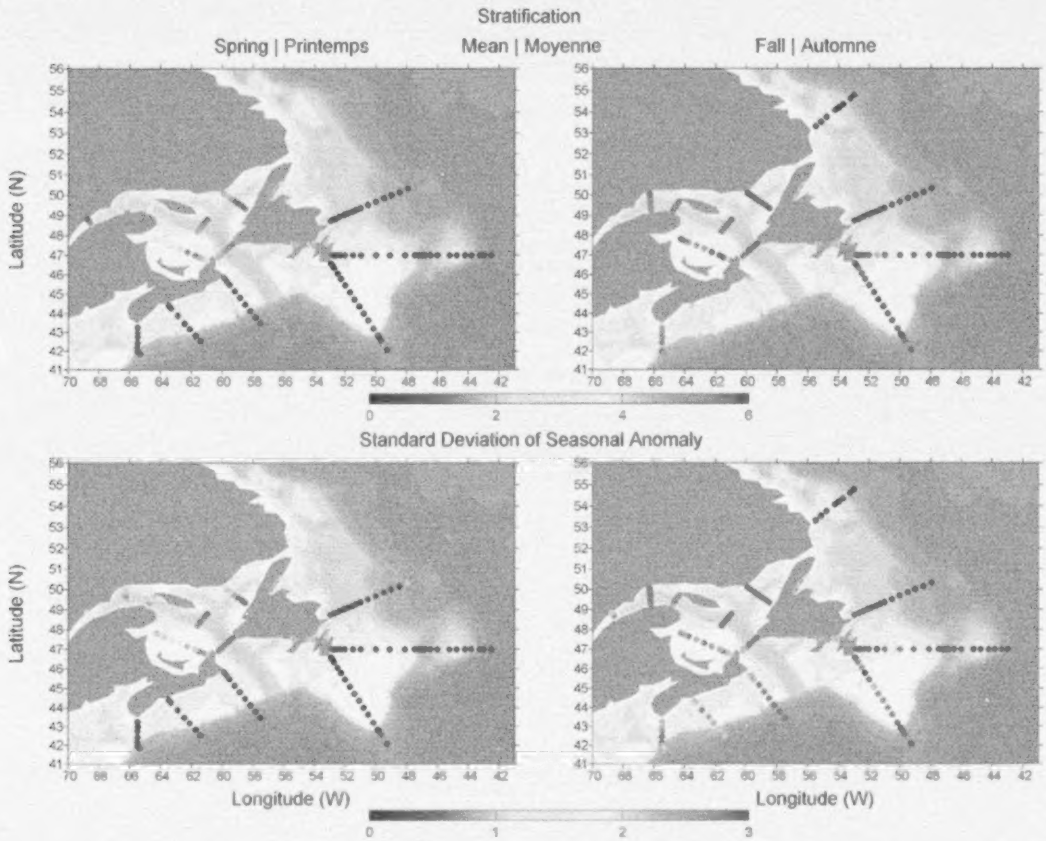

Figure E.9. Average stratification index (kg/m^3) and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

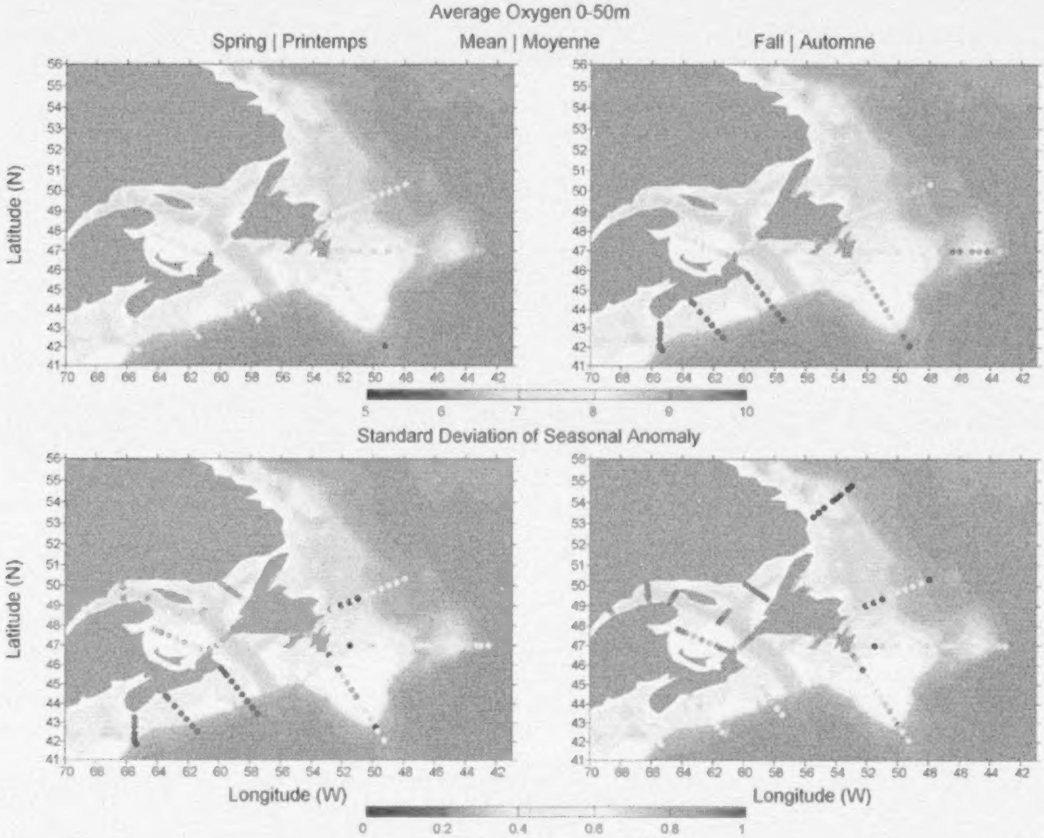

Figure E.10. Average oxygen concentration (mL L^{-1}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

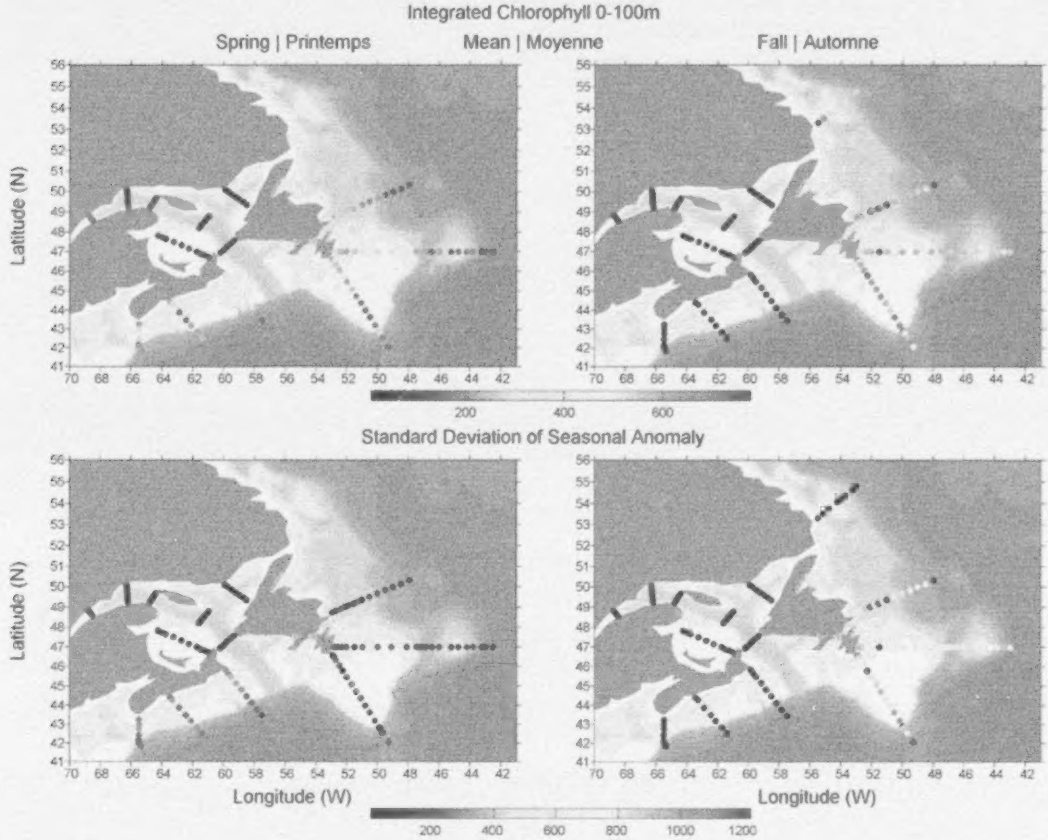

Figure E.11. Integrated chlorophyll concentration (mg Chl m^{-2}) min the layer 0-100 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

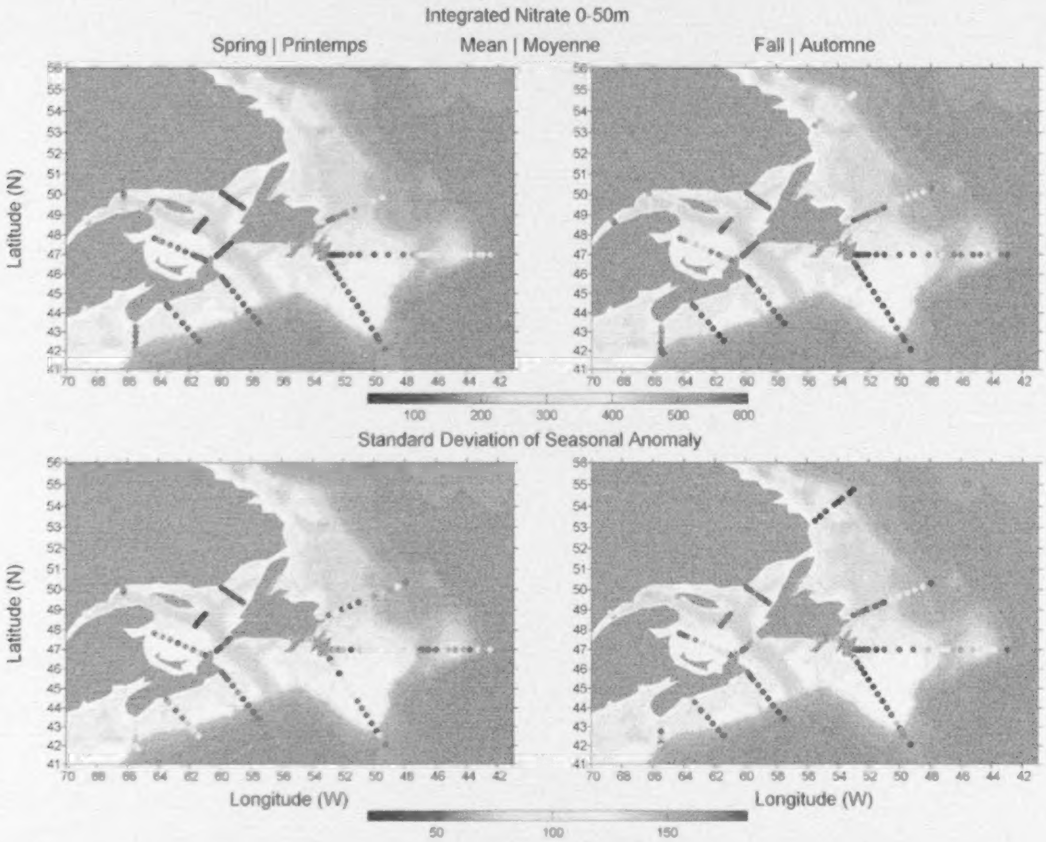

Figure E.12. Integrated nitrate concentration (mmol m^{-2}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

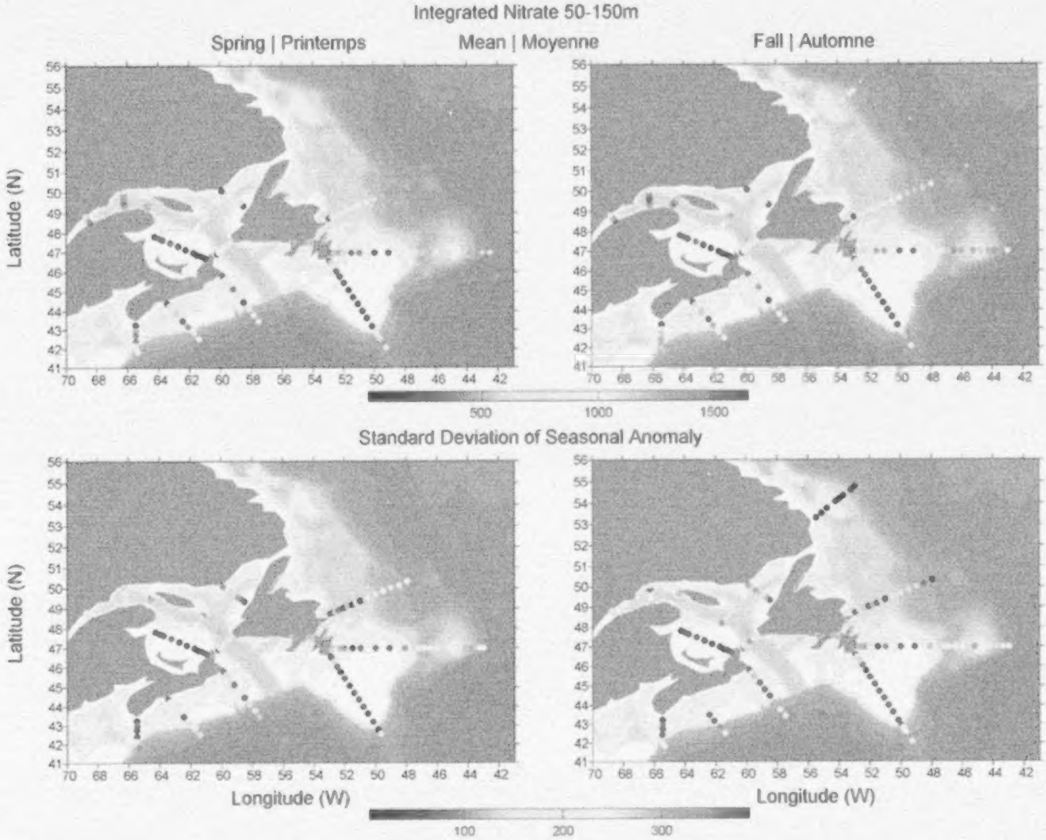

Figure E.13. Integrated nitrate concentration (mmol m^{-2}) in the layer 50-150 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

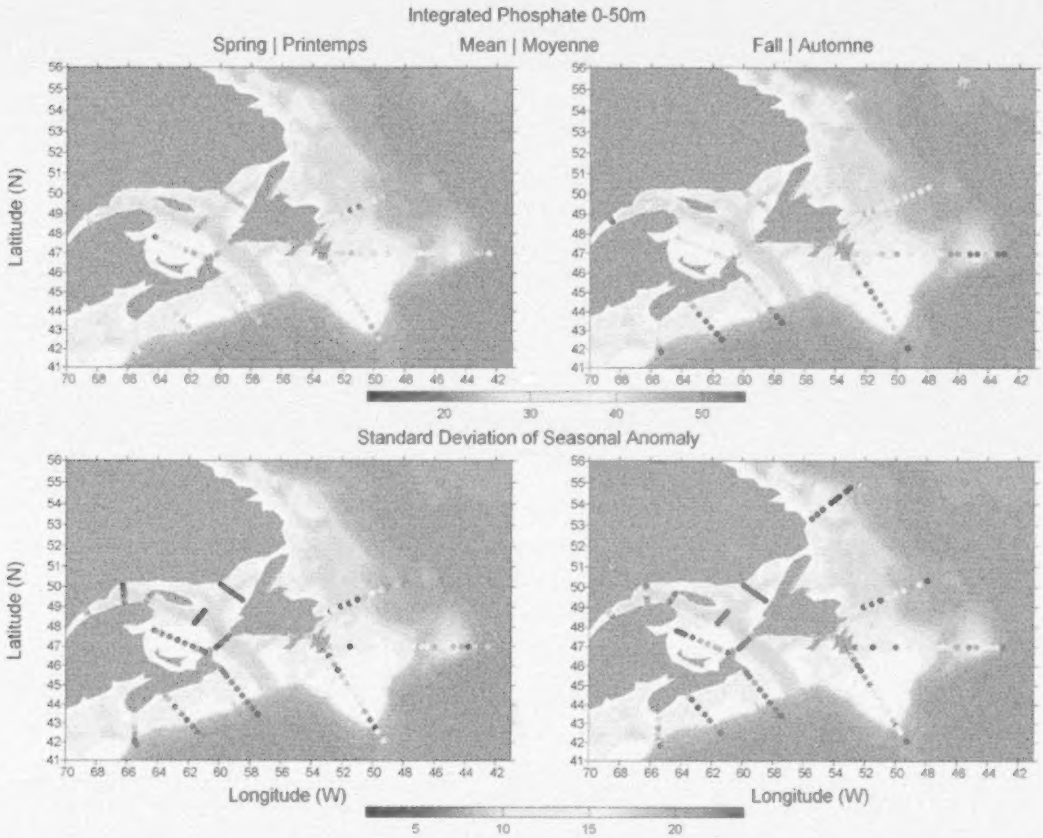

Figure E.14. Integrated phosphate concentration (mmol m^{-2}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

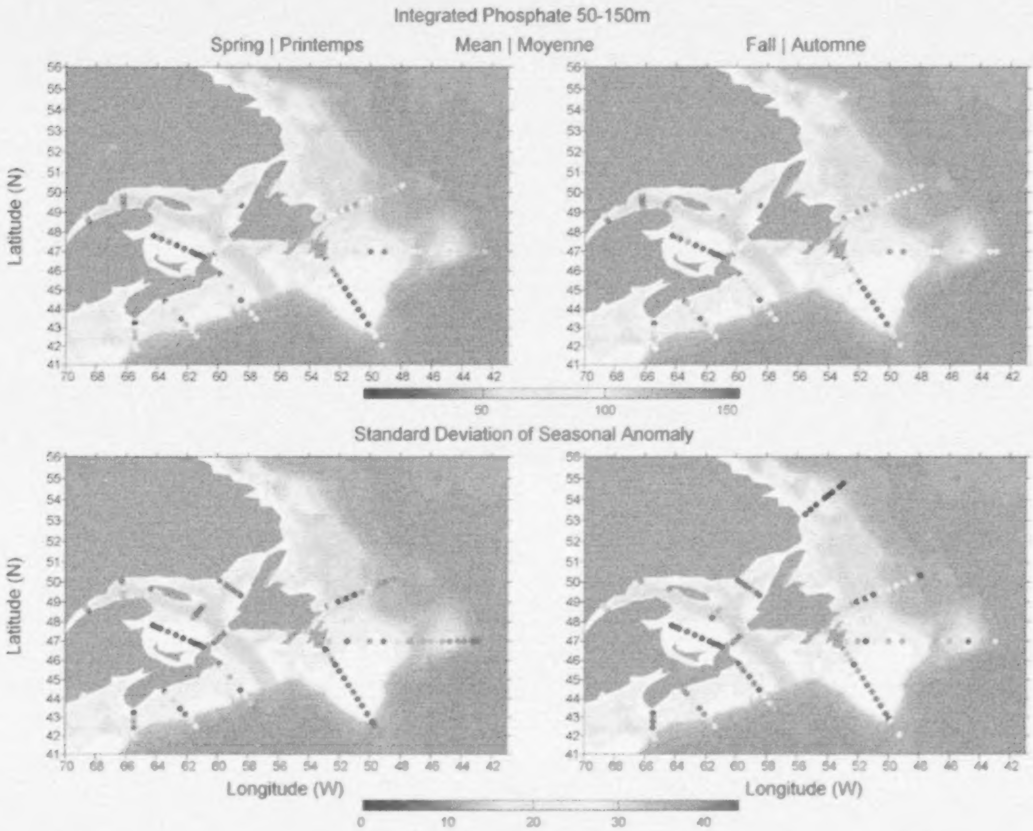

Figure E.15. Integrated phosphate concentration (mmol m^{-2}) in the layer 50-150 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

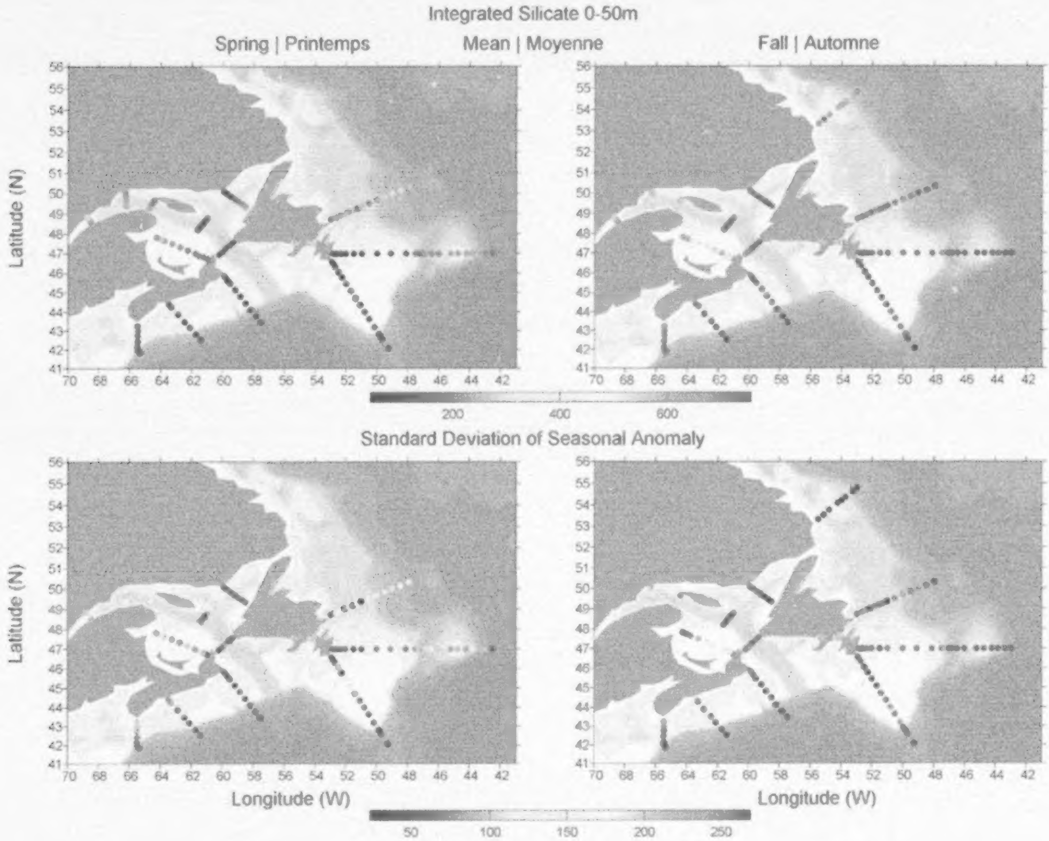

Figure E.16. Integrated silicate concentration (mmol m^{-2}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

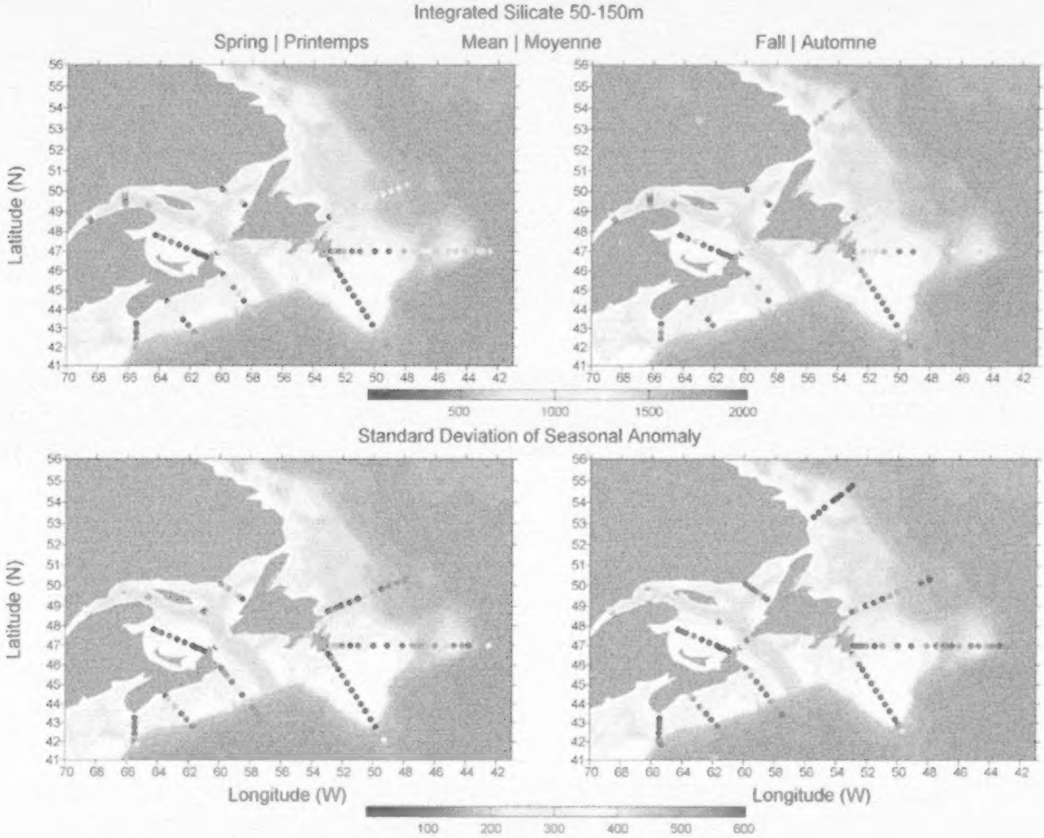

Figure E.17. Integrated silicate concentration (mmol m^{-2}) in the layer 50-150 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

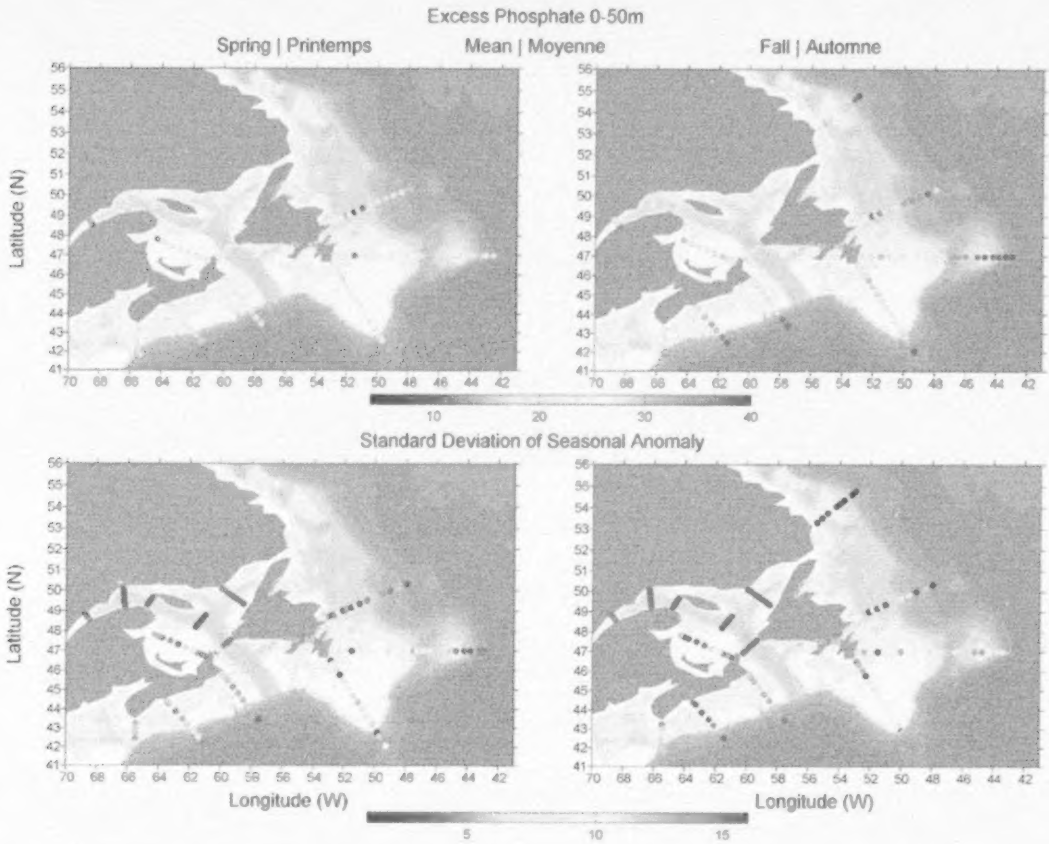

Figure E.18. Excess phosphate (mmol m^{-2}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.

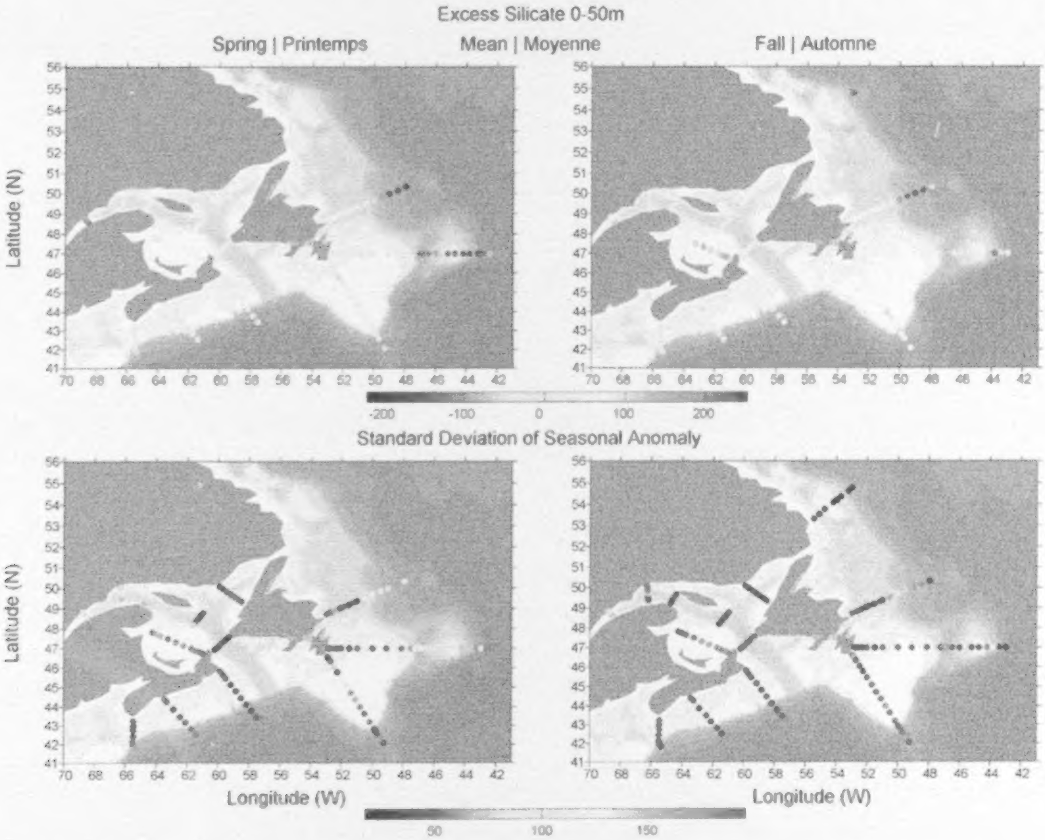

Figure E.19. Excess silicate (mmol m^{-2}) in the layer 0-50 m and standard deviation of seasonal anomaly at each AZMP station, 1999-2011.